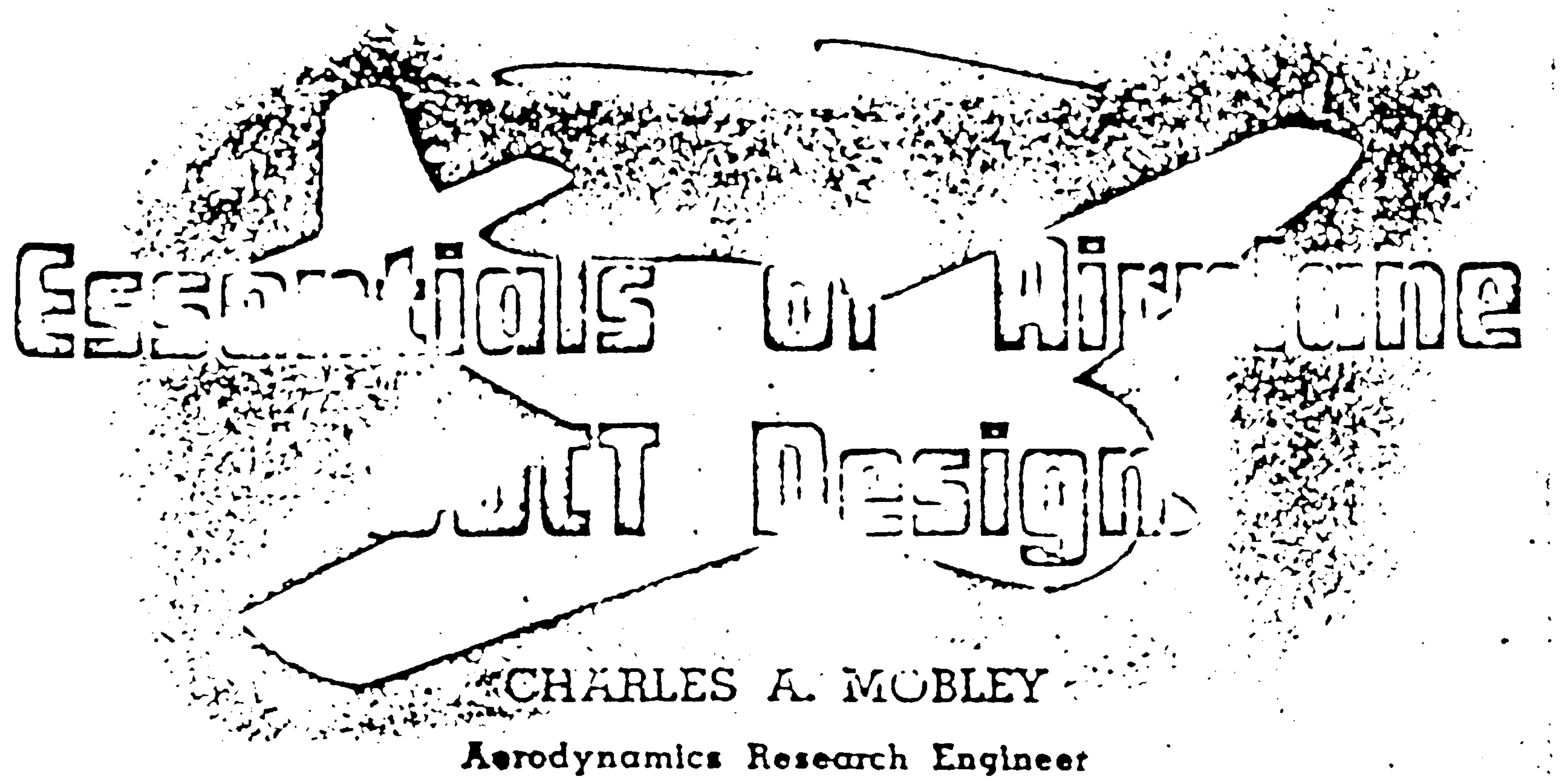

Essentials of Airplane Duct Design

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Airplane Weight Materially Reduced by Careful Engineering in the Design of the Duct Systems Supplying Air for Carburetion, Heating, Cooling and Ventilation —Reduction in Size also Provides More Useful Space within the Fuselage

AIRCRAFT duct systems for supplying air for carburetion, heating, cooling and ventilation must be carefully engineered so that their weight is held to a minimum and also will materially reduce the weight of an airplane and increase the useful space within its fuselage. Naturally, the volume of air is determined by the requirements of the purpose for which it is to be employed. In general the flow should be constant in all sections of the system, which should be as short and simple as possible consistent with good design. As losses in a duct system are directly reflected in increased drag of the airplane, the maximum engineering efficiency must be put into its design. While this article is not an exhaustive treatise on duct design, it does furnish considerable data of value in designing duct systems together with sufficient elucidation to facilitate their use. (A bibliography is added for the benefit of those desiring more complete coverage.)

The losses in airplane ducts may be divided into a number of types. The usual major divisions are: (a) Entry losses: Losses incurred in taking air from the airstream through an opening and into the airplane duct system. (b) Friction losses: Losses due to contact of the air with the internal duct surfaces. (c) Divergence losses: Losses that arise as a result of stream expansion caused by increase of area of the duct. (d) Corner or bend losses: Losses resulting from change of direction of the duct. (e) Contraction or nozzle losses: Losses arising from a reduction in duct area and the resulting stream contraction. (f) Obstruction losses: Losses due to obstructions passing through the duct or to duct distortion to avoid structure. Friction and contraction losses are usually very small in airplane ducts, provided reasonable care is taken to have smooth internal surfaces and if contractions are smoothly made. Entry, divergence, obstruction, and turn losses are frequently high, and this paper goes into considerable detail concerning the design of these parts of the duct system.

Internal duct losses increase as the square of the speed of the air through the duct. To avoid large losses, it is important that these internal velocities be kept low. For example, if a duct operating at 150 fps has the speed reduced to 75 fps, the loss in the duct will be only one-quarter as great.

The entry of the duct requires careful design to prevent high internal and external losses. From a practical standpoint, the entry serves to convert a part of the dynamic pressure, or kinetic energy of the airstream, into static pressure to push the air through the duct. In order to do this, the fast moving stream striking the entry must be expanded and slowed down. When the air velocity is reduced, the kinetic energy becomes, in part, an increase in static pressure. The ratio of the velocity through the entry to the velocity of the free airstream outside of the airplane is referred to as the velocity ratio of the entry. This ratio is often used to estimate the amount of external fairing needed for the entry and also the internal entry losses.

There are two ways in which this stream expansion may be accomplished and modifications and combinations of each suitable for different instances are given below.

(a) External expansion: The stream

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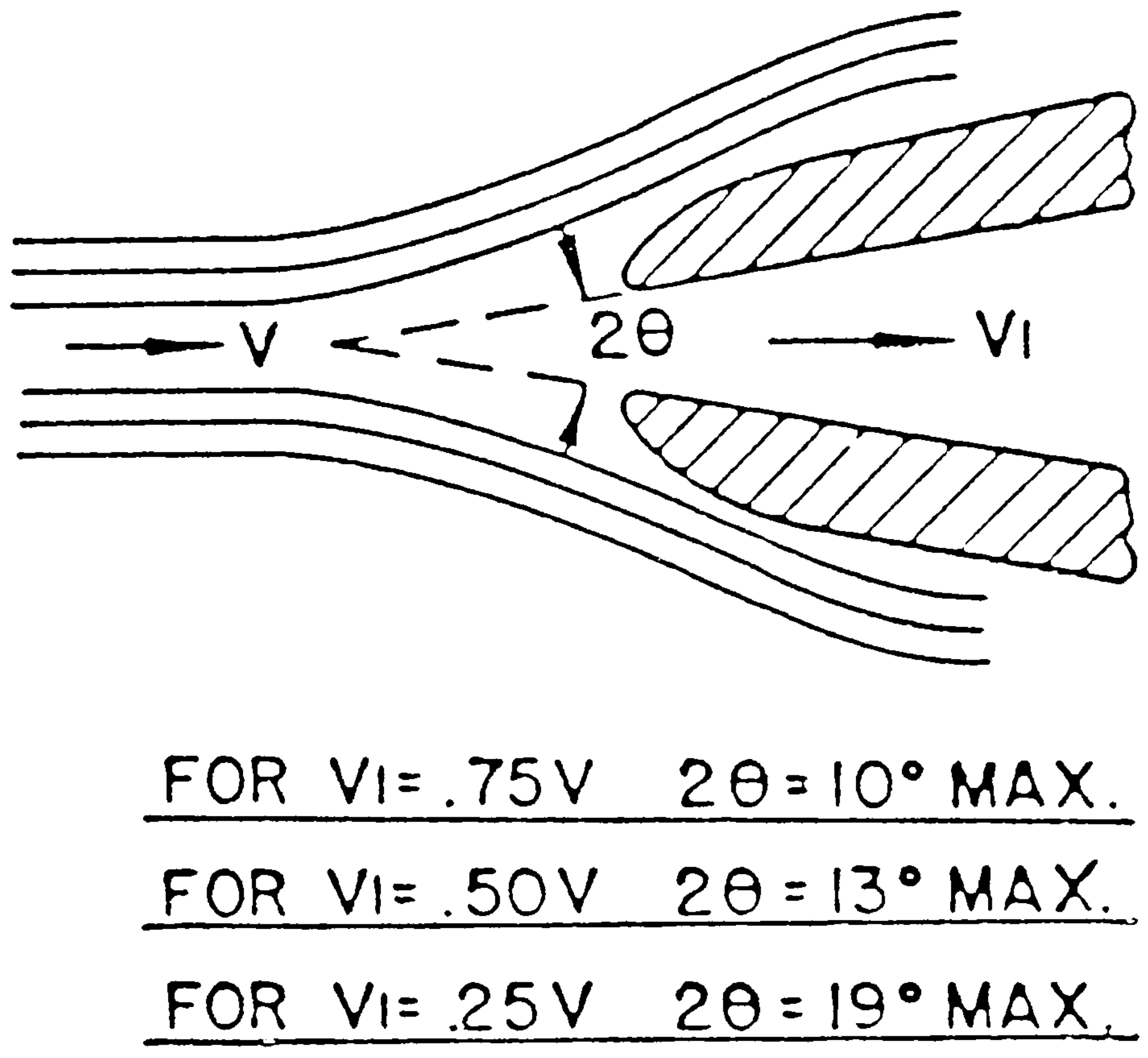
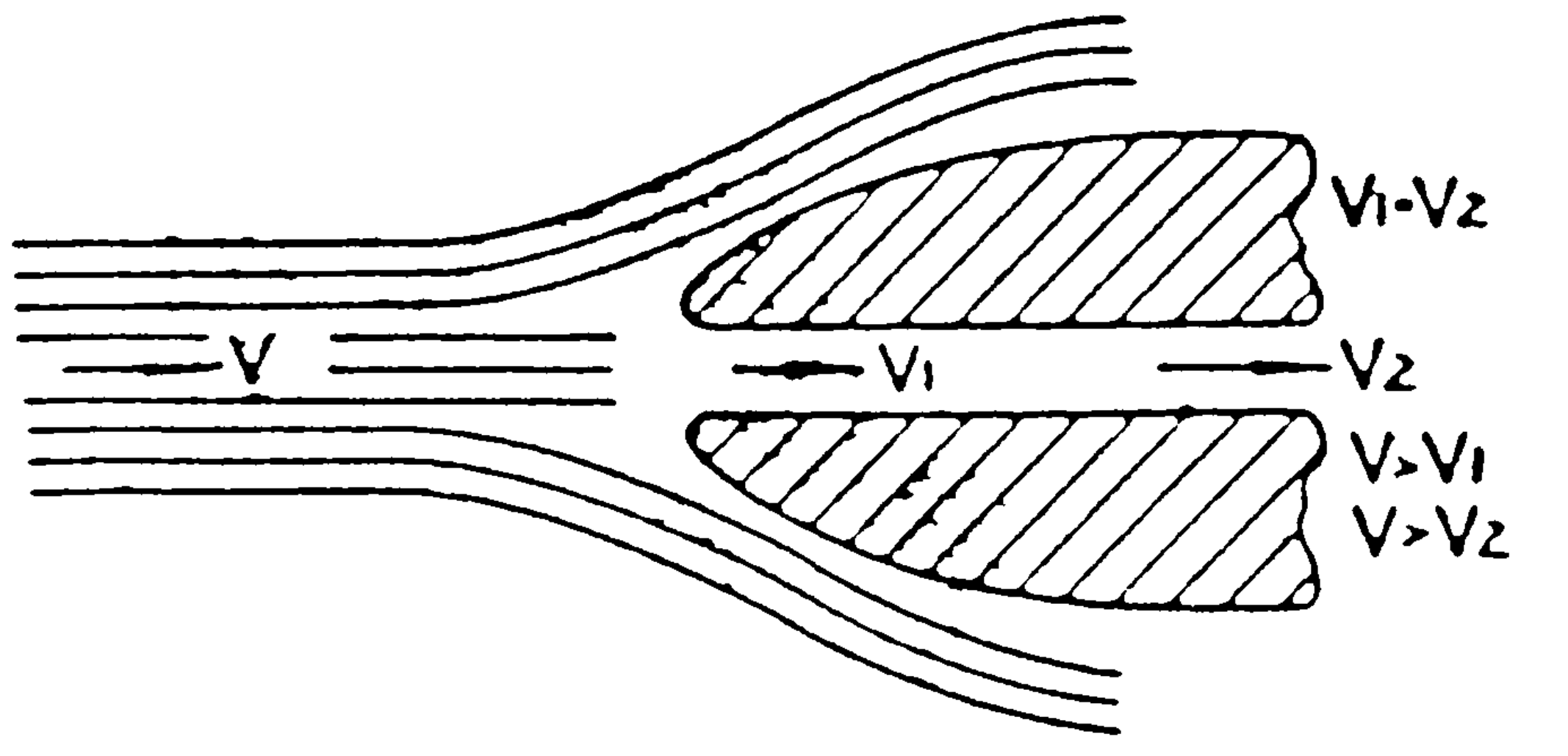

V
2θ
V₁
FOR V₁ = .75V 2θ = 10° MAX.
FOR V₁ = .50V 2θ = 13° MAX.
FOR V₁ = .25V 2θ = 19° MAX.

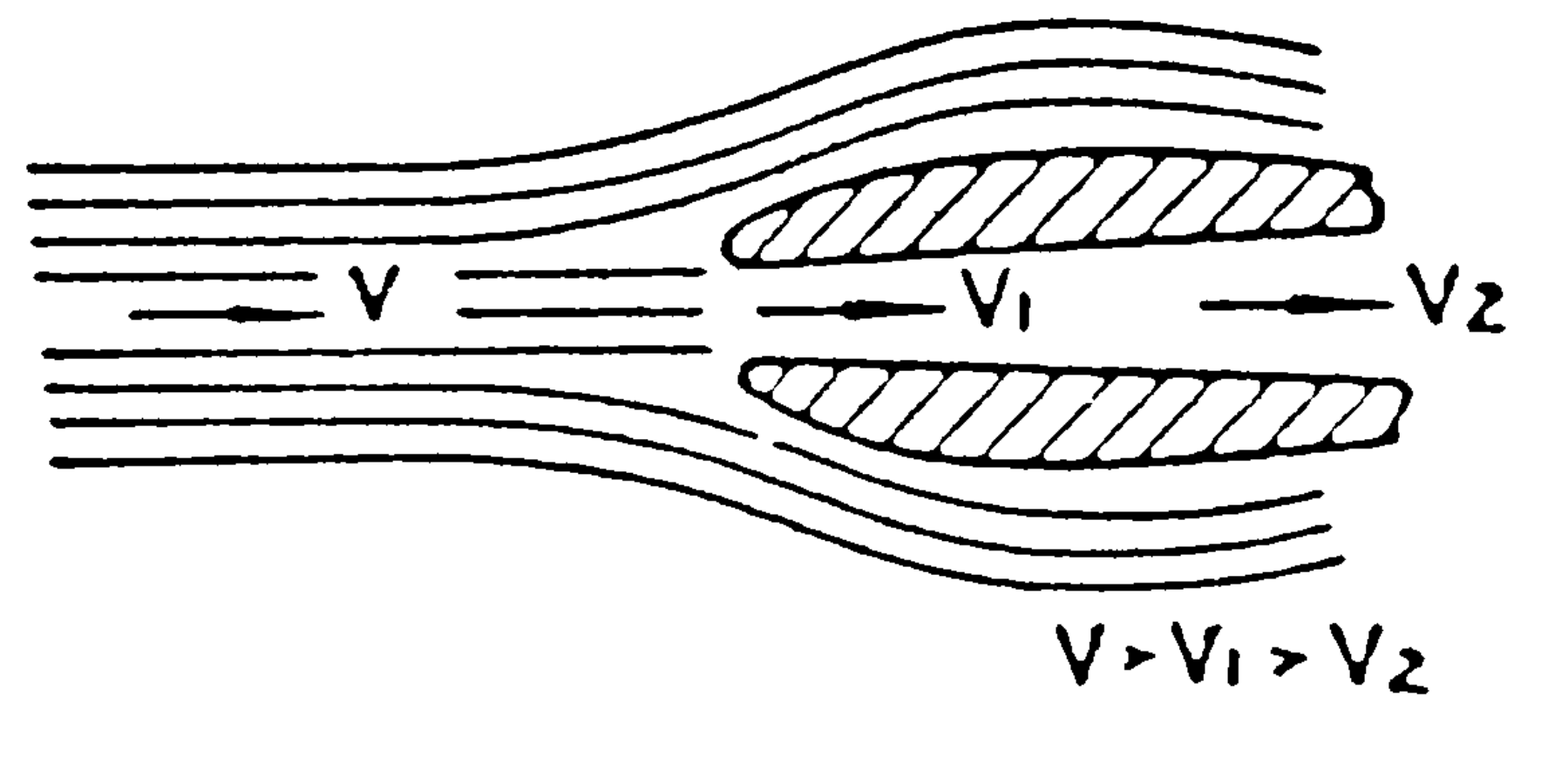
Figure 5

Figure 1

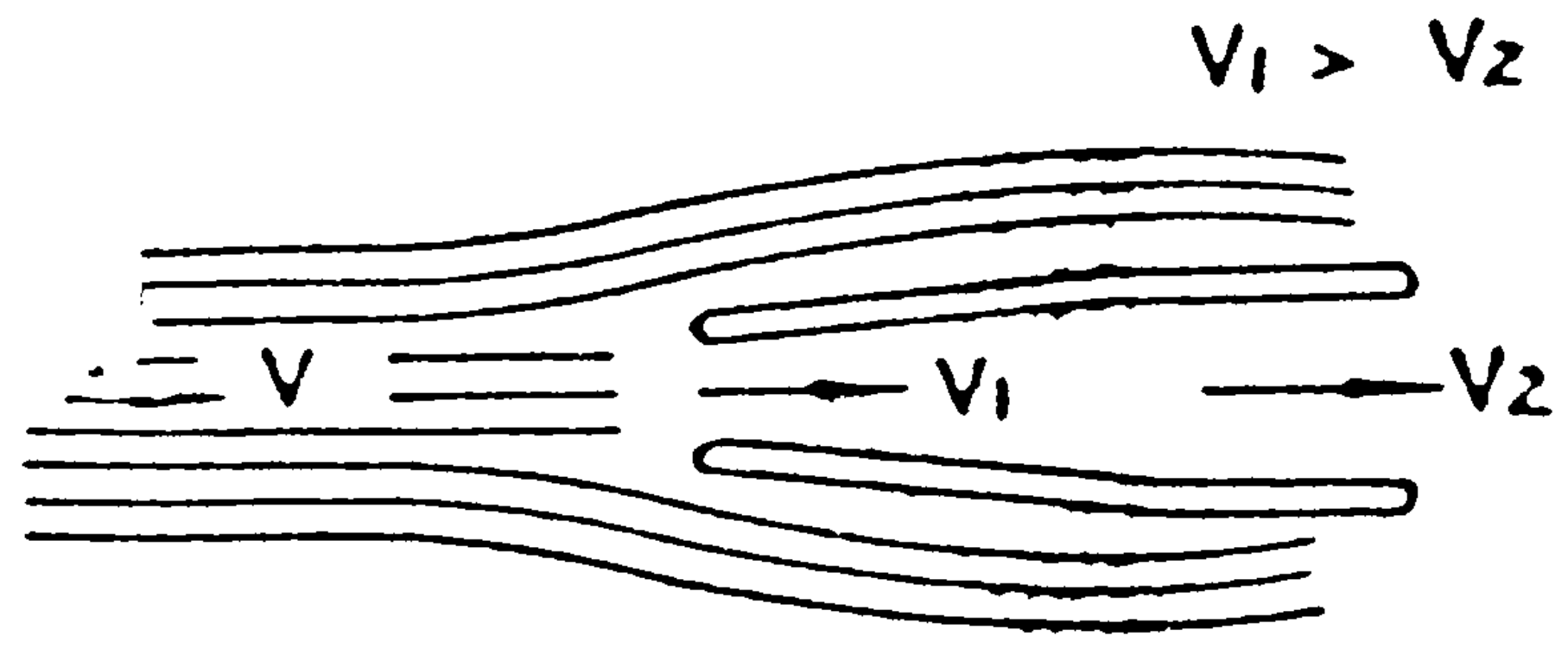


EXTERNAL EXPANSION

Figure 2

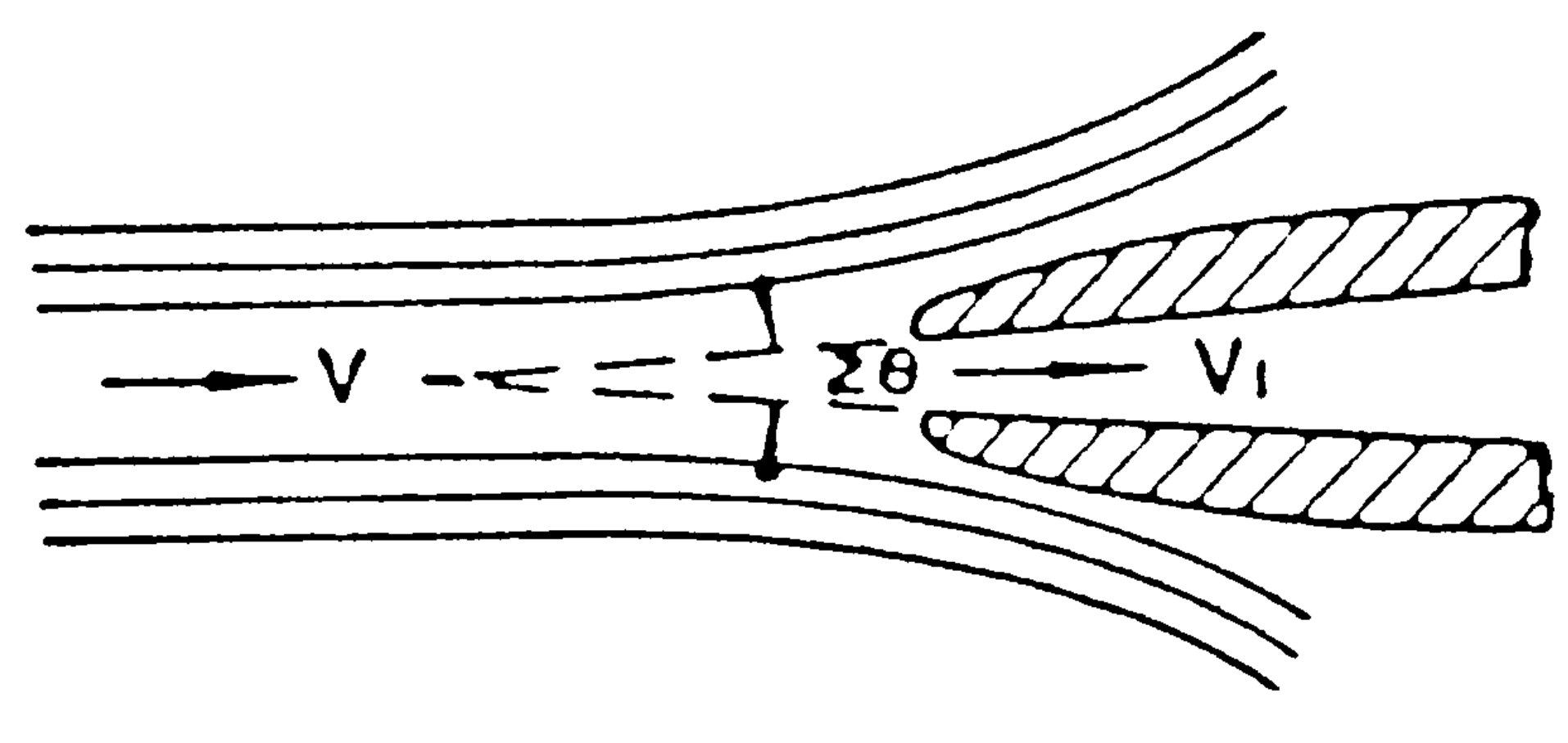


COMBINED EXTERNAL & INTERNAL EXPANSION



INTERNAL EXPANSION

Figure 3



FOR V₁ = V 2θ = 8° MAX

Figure 4

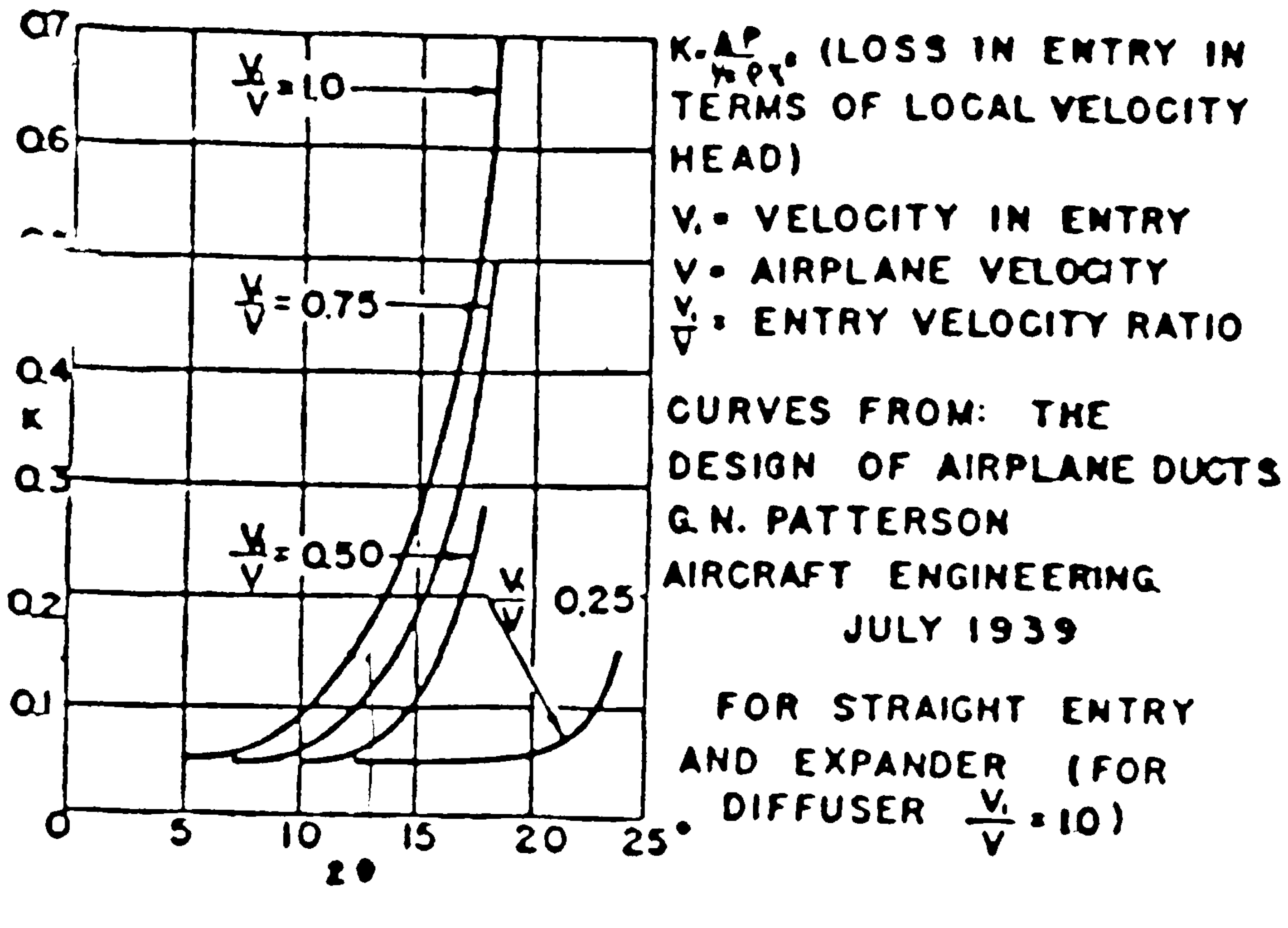


Figure 6

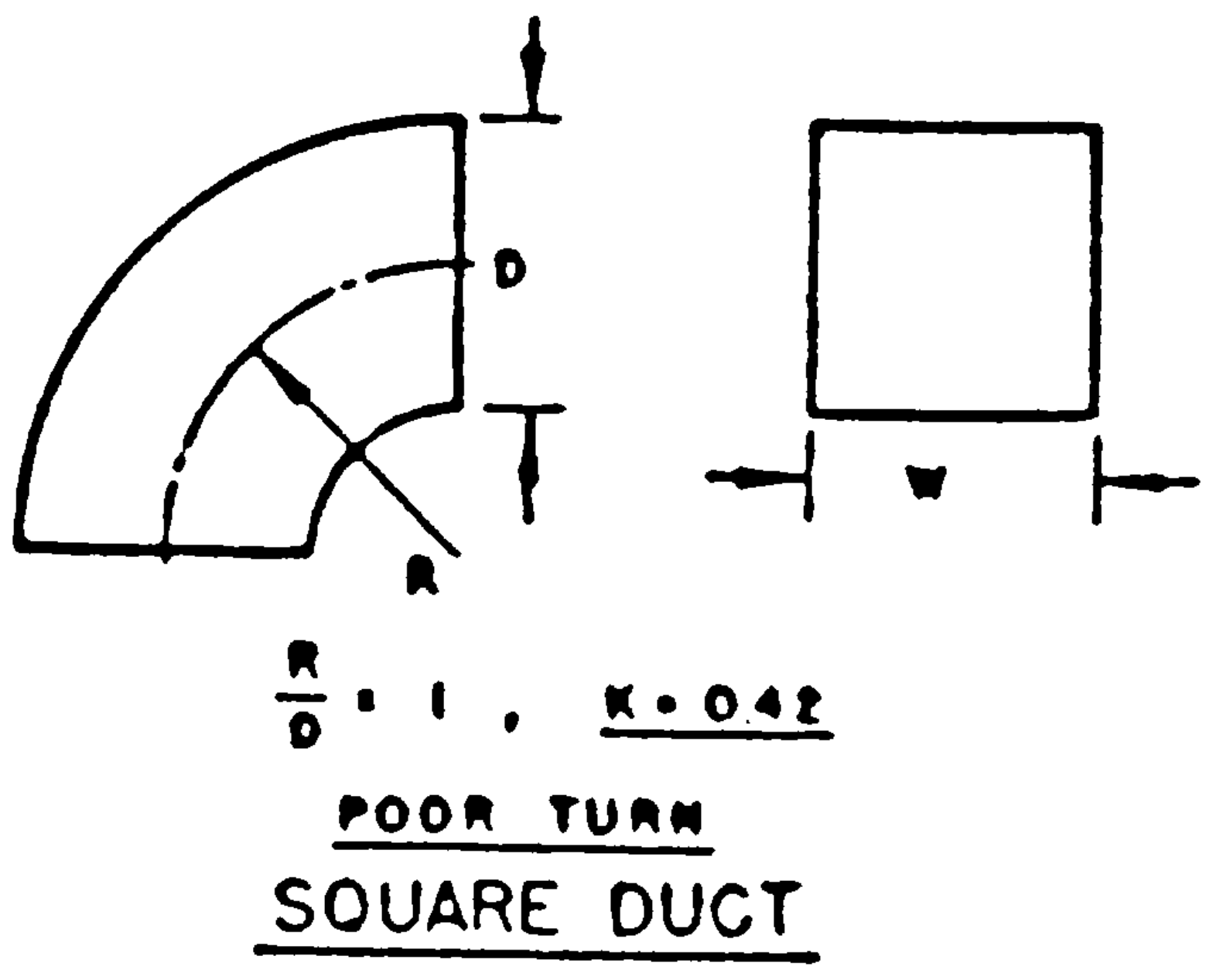


Figure 7

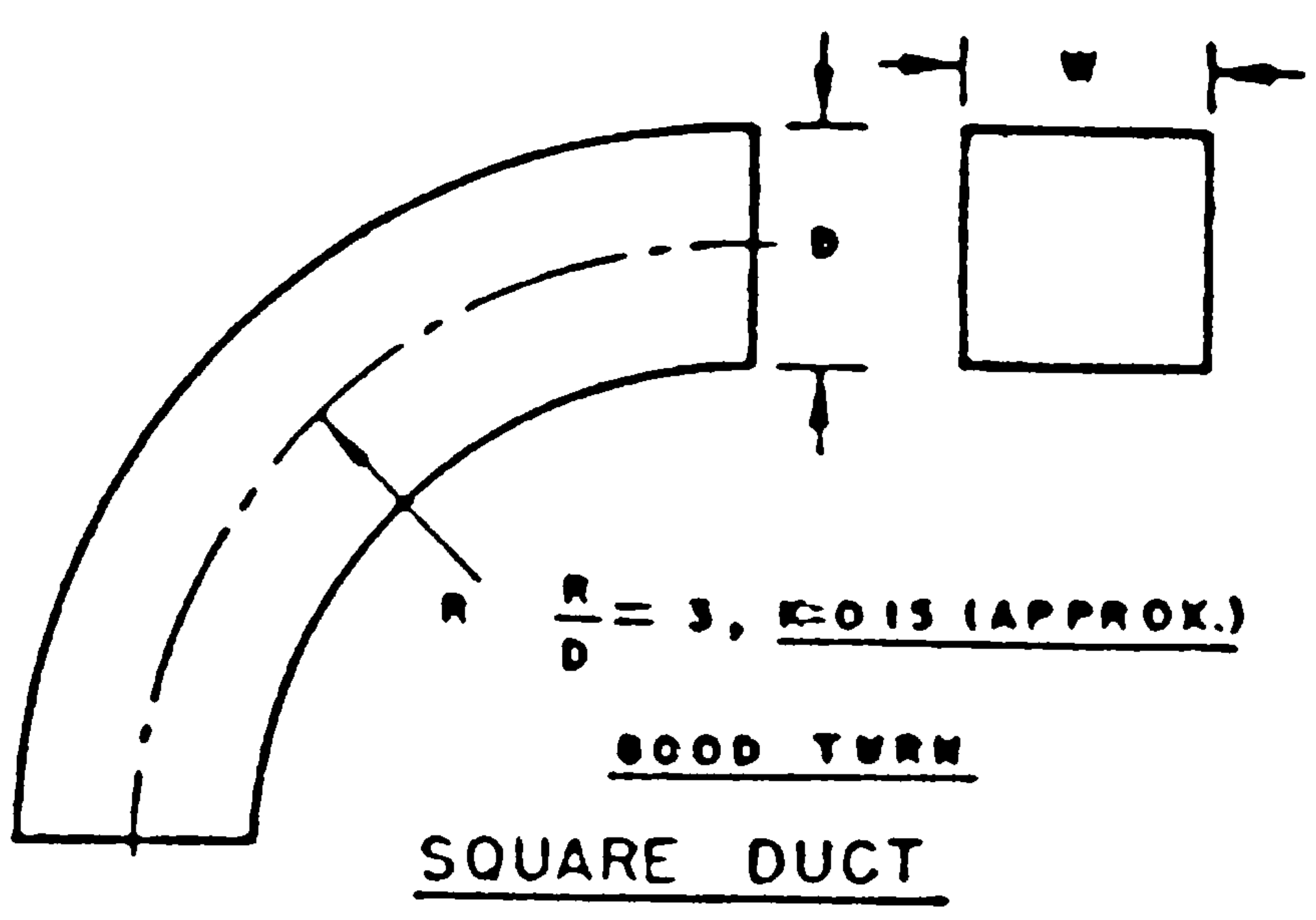


Figure 8

(*Continued from page* 122)

expansion and increase in pressure occur in front of the entry. This causes divergent streamlines and makes the use of heavy fairing necessary. In this case the duct has the same velocity as the entry, but these velocities are lower than the free stream velocity (fig. 1).

(b) Combined external and internal expansion: The stream expansion and increase in pressure occur partially in front of the entry and partially in the duct. In this case, the stream lines are less divergent and less fairing is necessary. The duct velocity in this case is lower than the entry velocity (fig. 2).

(c) Internal expansion: The expansion occurs entirely in the duct. Virtually no fairing is necessary and a sharp edge scoop may be employed. In this case the entry velocity is equal to the free stream velocity, but the duct velocity is low (fig. 3).

Amount of Expansion

This raises the question as to how much expansion to use. Since expansion of the walls at a faster rate than the air will follow introduces very high losses, the following sketches have been made to serve as a guide. The angles of divergence indicated can only be used when the air striking the entry has previously not been disturbed.

When the velocity is high in the entry, the allowable angle of divergence is lowest. For $V_1 = V$ $2\theta = 8^\circ$ max. (fig. 4). (2θ means angle of divergence.)

When the velocity is lower in the entry, greater angles of divergence may be used since the lower entry velocity causes external divergence of the oncoming streamlines. The continued divergence of the lines after they pass the entry is therefore easier (fig. 5).

Since losses from inadequate fairing are higher with low entry velocity, due to separation of flow, it is advisable to avoid too low a velocity ratio unless massive natural fairings are available. On the other hand, a high entry velocity may give high internal entry losses, particularly if large stream expansion is necessary following the entry. Therefore, in the usual case, it is generally best to select an entry velocity ratio of the order of .4 to .75 and to combine internal and external stream expansion for greatest efficiency.

If a design incorporating both internal and external stream expansion is arrived at, we can expect very good efficiency. In this case the moderate divergence of streamlines in front of the entry assists in moderate internal expansion, and a medium amount of fairing will prevent large external losses. Fairing needed is also reduced since the area of the opening is smaller than would be the case if no internal expansion took place.

Having decided the type of entry to use, and given the quality of air required, we can determine directly the amount of entry area needed. The intake velocity is determined by the type of entry selected. For example:

Q = Air required = 2500 cfm = 41.7 cfs
V = Plane speed 300 mph = 440 fps
Entry velocity ratio $V_1/V = .5$
$V_1 = 220$ fps
$Q = AV$

$$A = \frac{Q}{V} = \frac{41.7}{220} = .189 \text{ sq ft} = 27.2$$

sq in area required.

Note that the selection of velocity ratio in this example is entirely arbitrary. If large natural fairings are available, such as the leading edge of a wing, it would probably be advantageous to select a velocity ratio much smaller, such as .25 or even less. If no natural fairing is to be had and entry must be so located that the addition of fairing must be kept to a minimum, a higher velocity ratio may be necessary to keep external losses low.

Special Case of the Diffuser

The expansion area back of the entry is a special case of the diffuser (In the case of expansion following the entry considerable latitude is available due to the help of divergent lines of flow in front of the entry.) However, with an area of stream expansion following a straight section of pipe, it is necessary to limit the expansion angle of 2θ to the same figure used when the expander velocity ratio $V_1/V = 1.0$. The value

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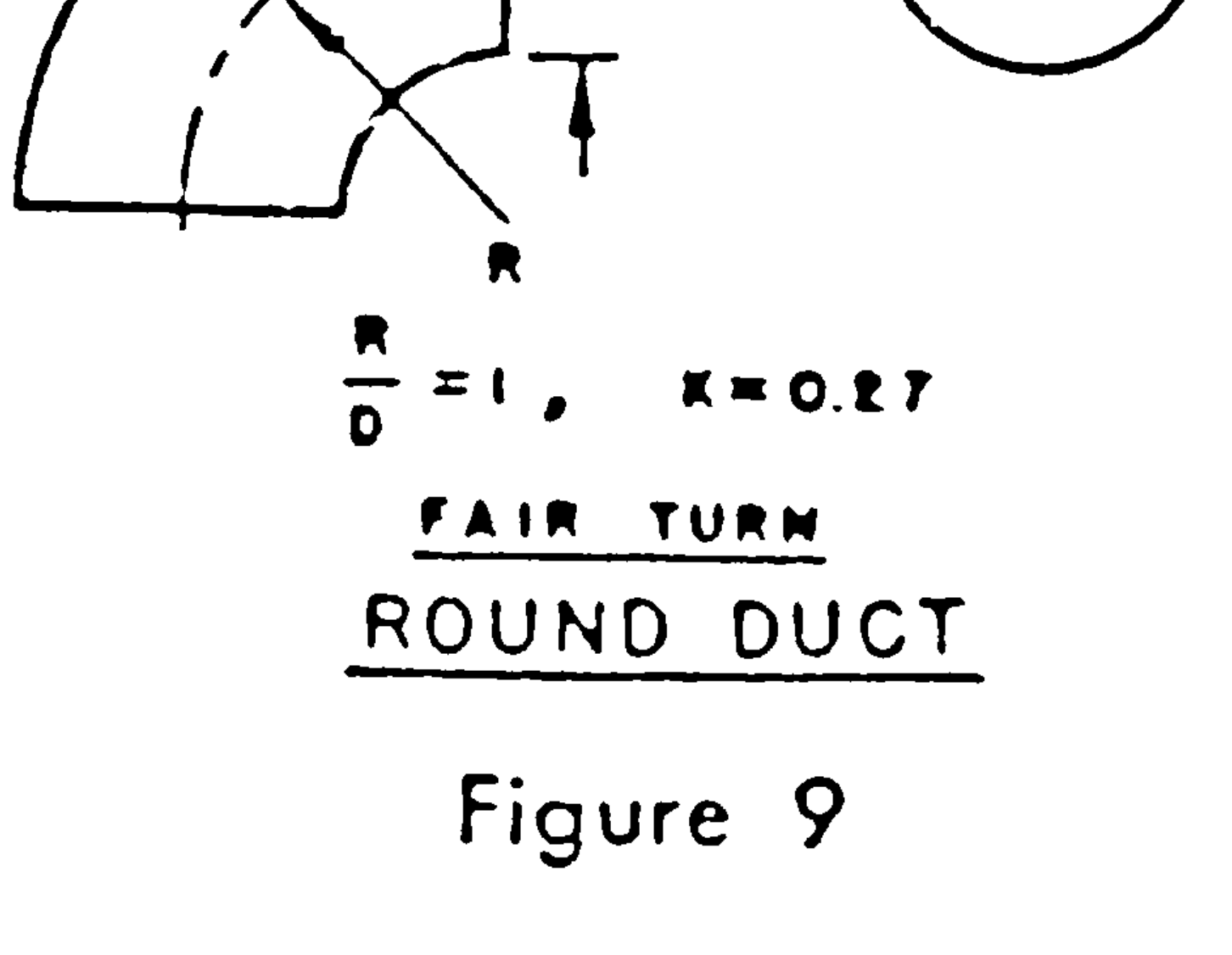
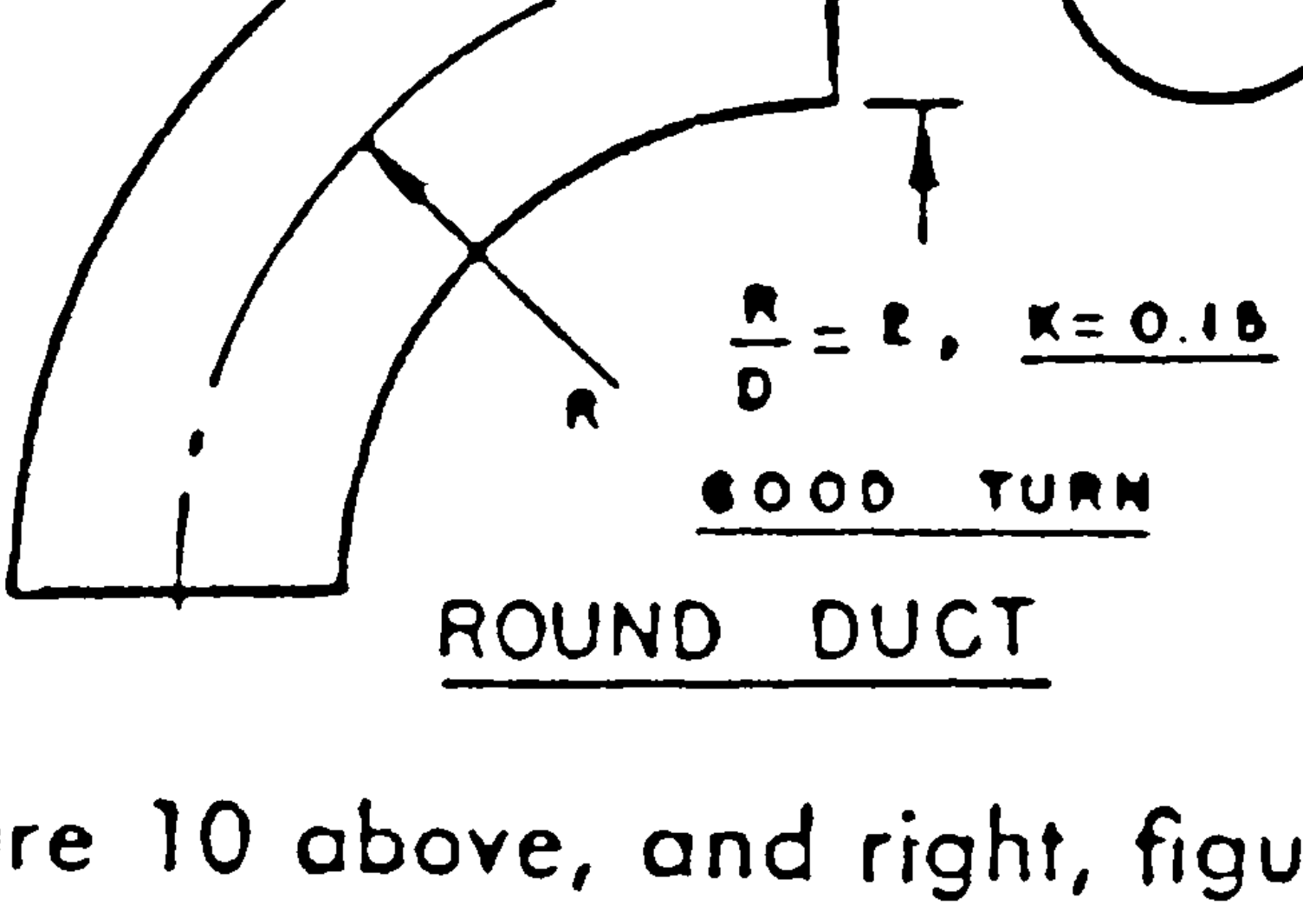


Figure 9



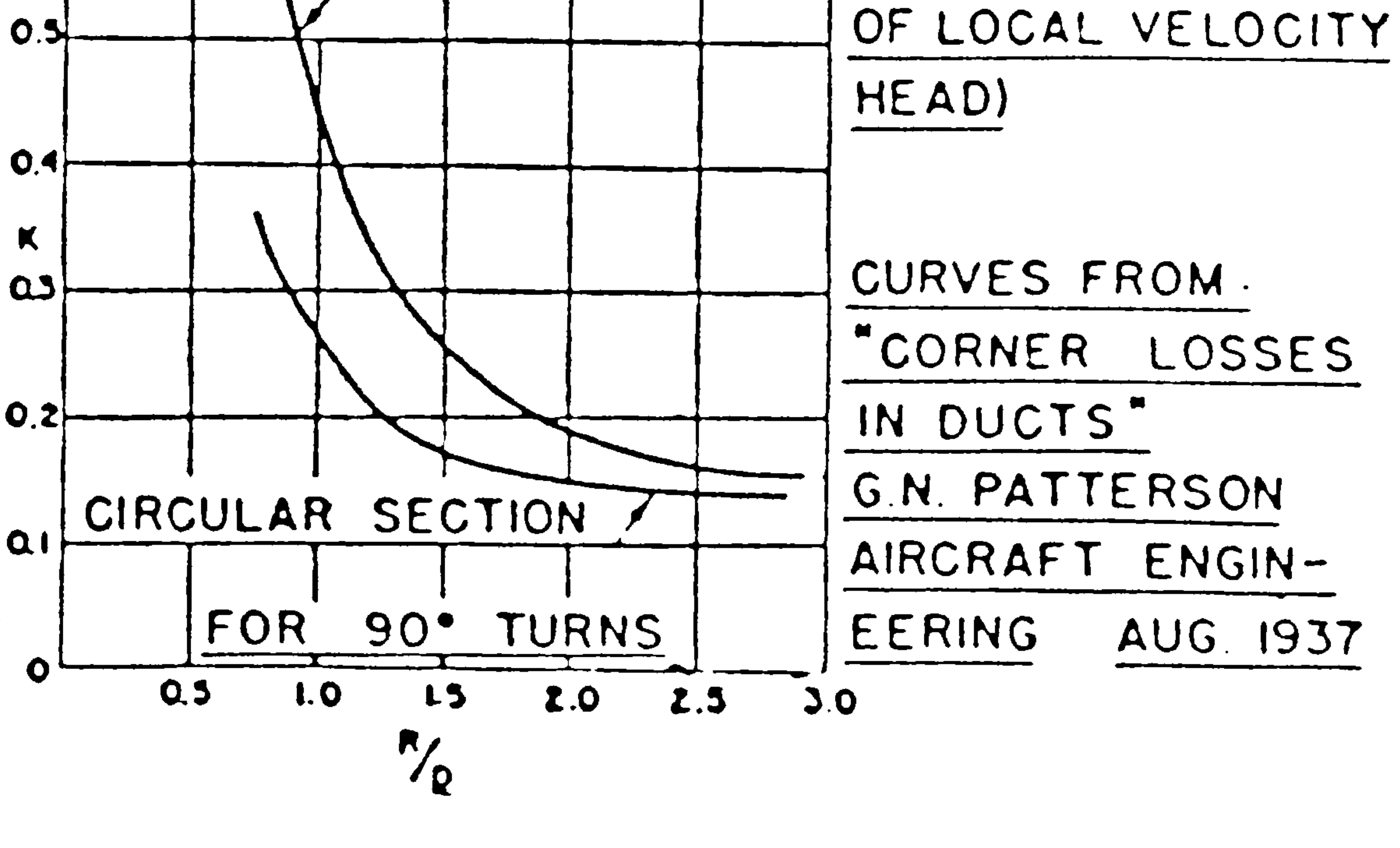


Figure 10 above, and right, figure 11

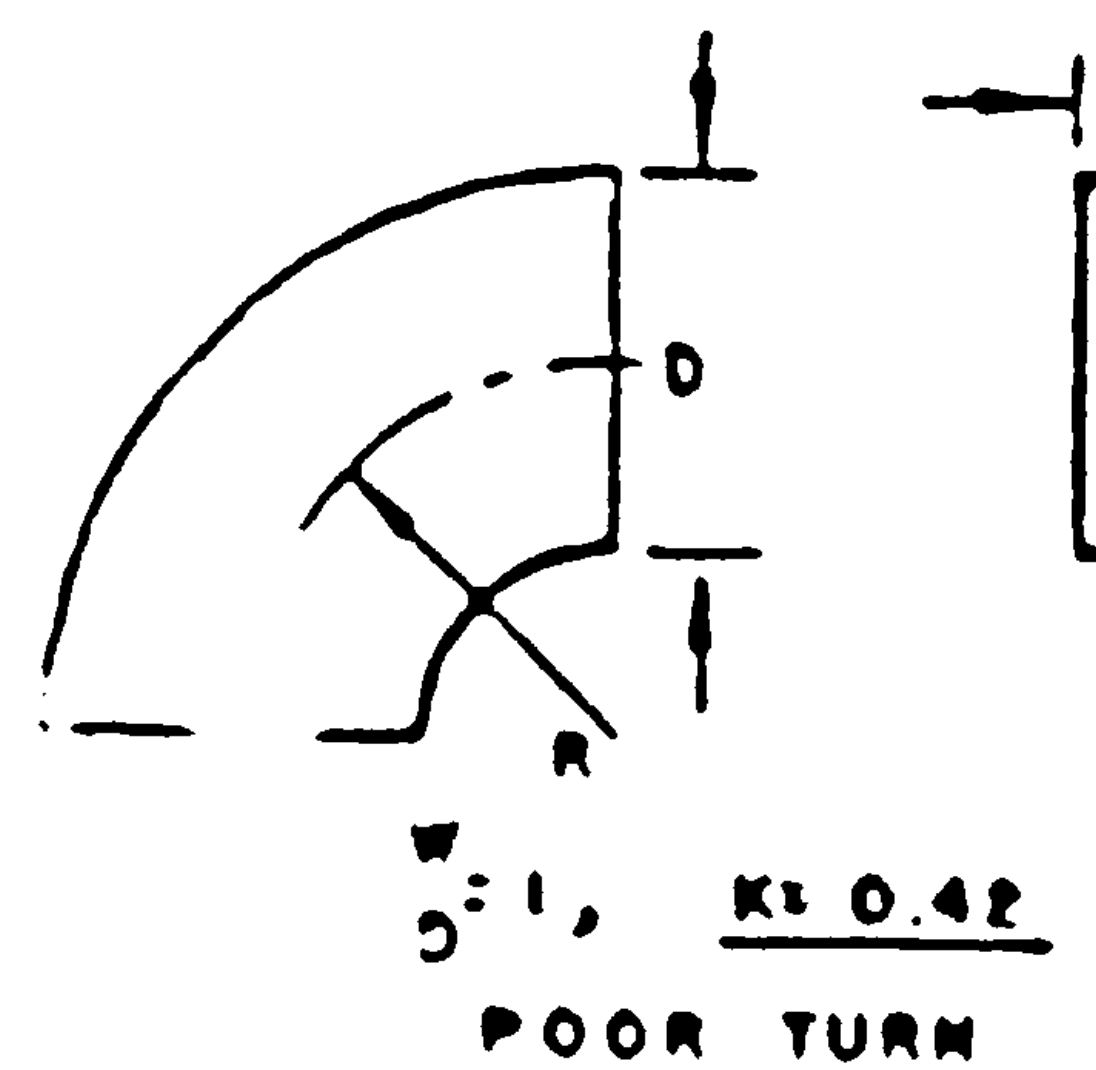


Figure 12

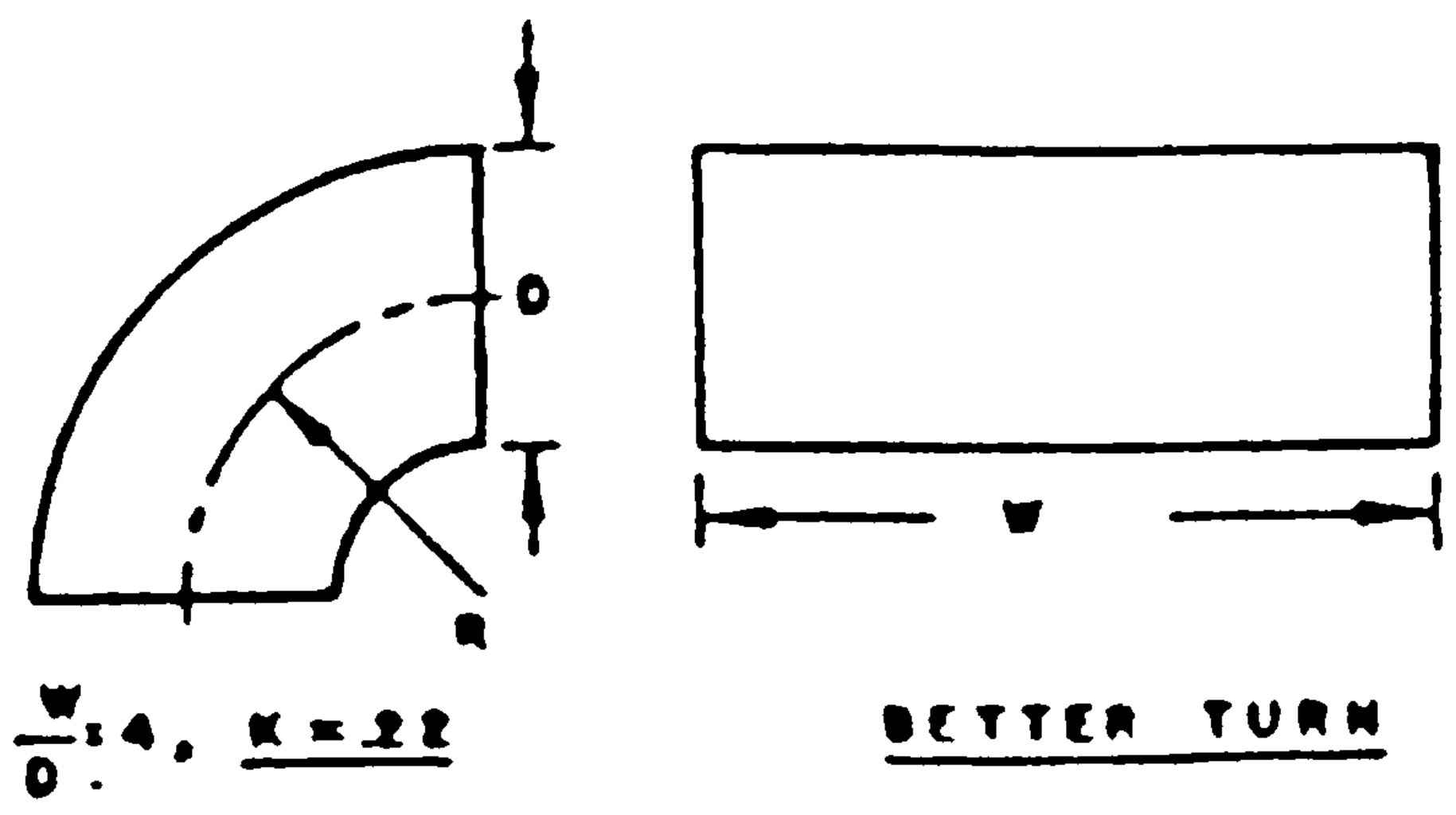


Figure 13

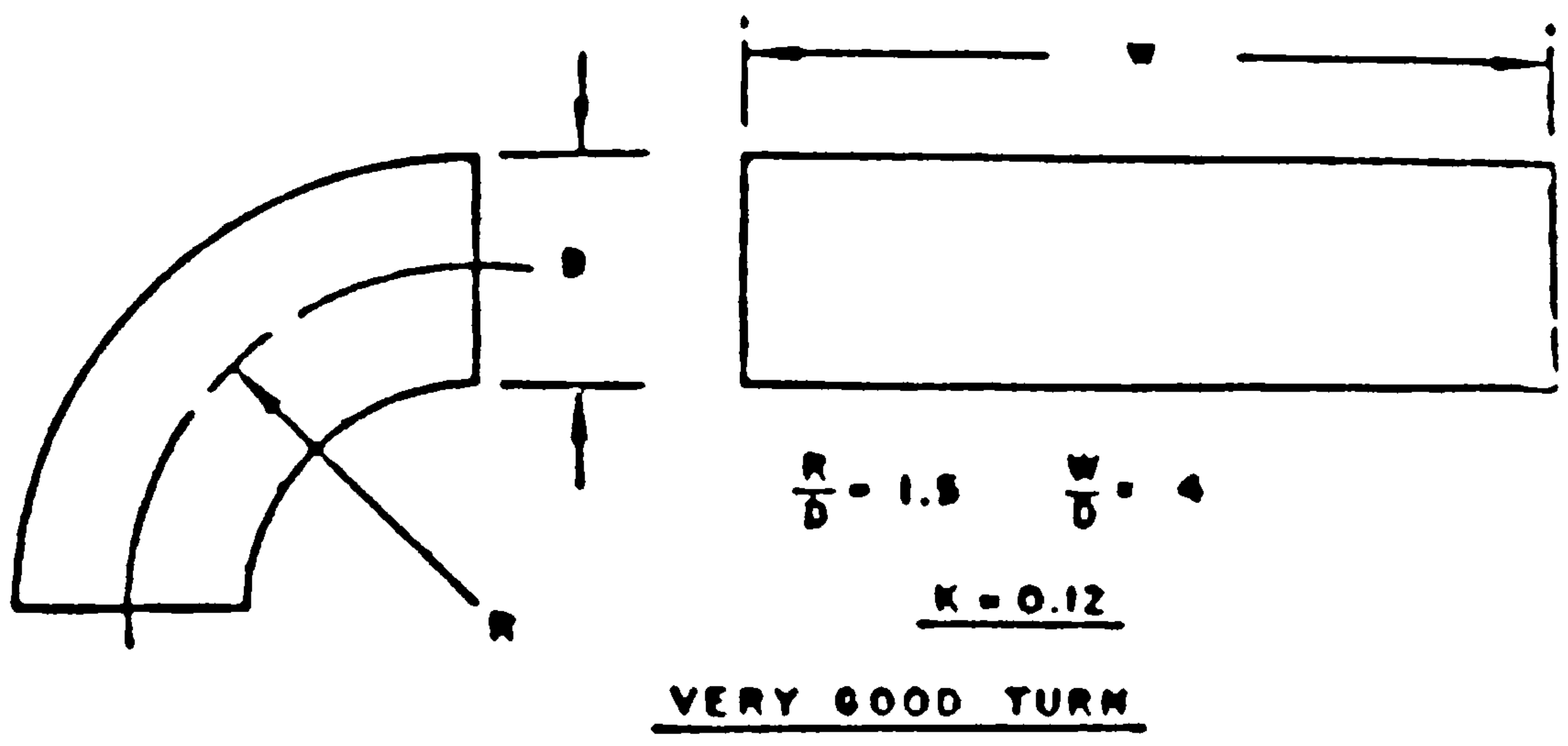


Figure 14

(*Continued from page* 124)

of 2θ should not ordinarily exceed 8° and, since it is not unlikely that the airflow will have some disturbances in it ahead of the diffuser section, it is well to keep $2\theta = 5°$ (fig. 6).

Obstructions are to be avoided if at all possible since losses of many kinds can originate due to blockage and deflection of flow. Interferences with the airplane structure call for rerouting the duct to avoid the structure or for fairing the interfering structure. If obstruction is of sufficient size to cause an appreciable percentage of blockage the fairing should be done according to diffuser rules to prevent the expansion beyond the obstruction from taking place at too fast a rate (fig. 6).

Probably the most critical point in duct design is the turn. Without a clear picture of the factors affecting turn efficiency, an otherwise well designed duct system can have very high losses. In order to evaluate the relative efficiency of a turn a factor is used expressing the loss as a pressure drop through the turn as referred to the *local* dynamic pressure. This factor is constant over a wide velocity range, and can be used in connection with all parts of the duct system to evaluate losses.

$\Delta_p = K\frac{\rho}{2} V_t^2$ where K = loss factor
Δ_p = pressure drop through turn
ρ = air density through turn
V_t = velocity in turn

This equation shows the importance of having as low an internal velocity as practical. Since K is a constant the pressure drop will be sharply reduced when this internal velocity is reduced. For turns of less than 30° the type of turn is not very important, as all such turns will show small losses.

From table I it can be seen that the losses increase very rapidly as the angle of the turn goes above 30°. However, by careful design turns of low loss for large angles of turn can be produced. This is done through choosing proper shapes to fit conditions, as there are several methods whereby a bad turn may be made into a good one. Some examples of 90° turns, both good and bad follow:

Effect of radius ratio. Radius ratio is the radius of the center line of the turn divided by the depth of the duct measured in the same plane (figs. 7, 8, 9, and 10). From these figures it can be seen that increasing the radius of the turn decreases losses sharply. In fig. 11 are given two curves showing variation of K with radius ratio.

Increasing Aspect Ratio

Effect of aspect ratio. (Aspect ratio is the width of the duct divided by its depth.) Note that $\frac{R}{D}$ previously discussed is held constant at a value of one to show effect of aspect ratio $\frac{W}{D}$ (figs. 12 and 13.) It will be seen that increasing aspect ratio decreases turn loss. Combining the effects of radius ratio and aspect ratio can result in a very low turn loss (fig. 14).

In fig. 15 is given a set of curves for various aspect ratios plotted against radius ratio and loss factor. From these curves efficient turn shapes can be selected to meet almost any condition. In airplane ducting instances will occur, where, due to space limitations, it is not feasible to use either high aspect ratio or radius ratio. This condition is not as hopeless as it may seem at first, since such a turn can be improved internally by using dividers to split the turn into two or more turns of improved aspect and radius ratio or by making a square turn and using vanes (figs. 16 and 17).

The average K from calculation gives

$$\frac{.29 + .15}{2} = .22$$

The actual K will be somewhat higher due to added losses of blockage and surface friction of the divider and will be approximately K = 0.30. However, the turn losses have been reduced to approximately 40% of what they were without the divider and we have a good turn. The number of dividers should be kept low to reduce blockage and friction.

Where it is impossible to use high aspect and radius ratios and where high efficiency is desired, the vanes previously mentioned may be introduced into a square turn (fig. 18).

The vanes are 1/4 circle arcs. $\alpha = 45°$

The gap chord ratio $\frac{S}{C} = 0.45$ (optimum) (see reference 5)

$K = 0.20$ (approximately)

In general the chord chosen should be rather large so that fewer vanes will be needed to obtain the optimum $\frac{S}{C}$ and thus the blockage and friction losses will be kept down. The effect of vanes is exactly the same as the divider in that the turn is broken up into two or more turns of good aspect and radius ratios.

(*Continued on page* 128)

Figure 15

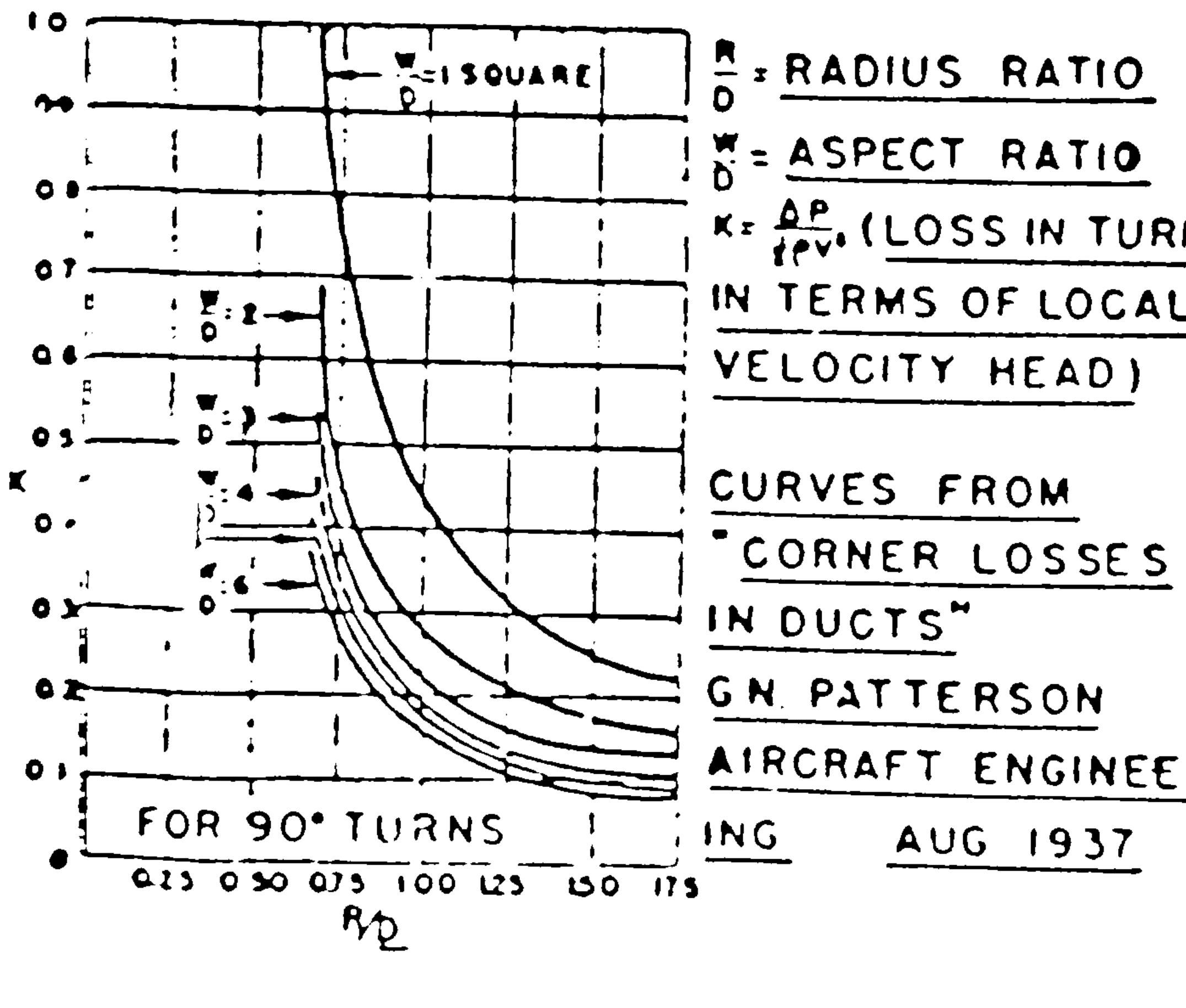


Figure 16

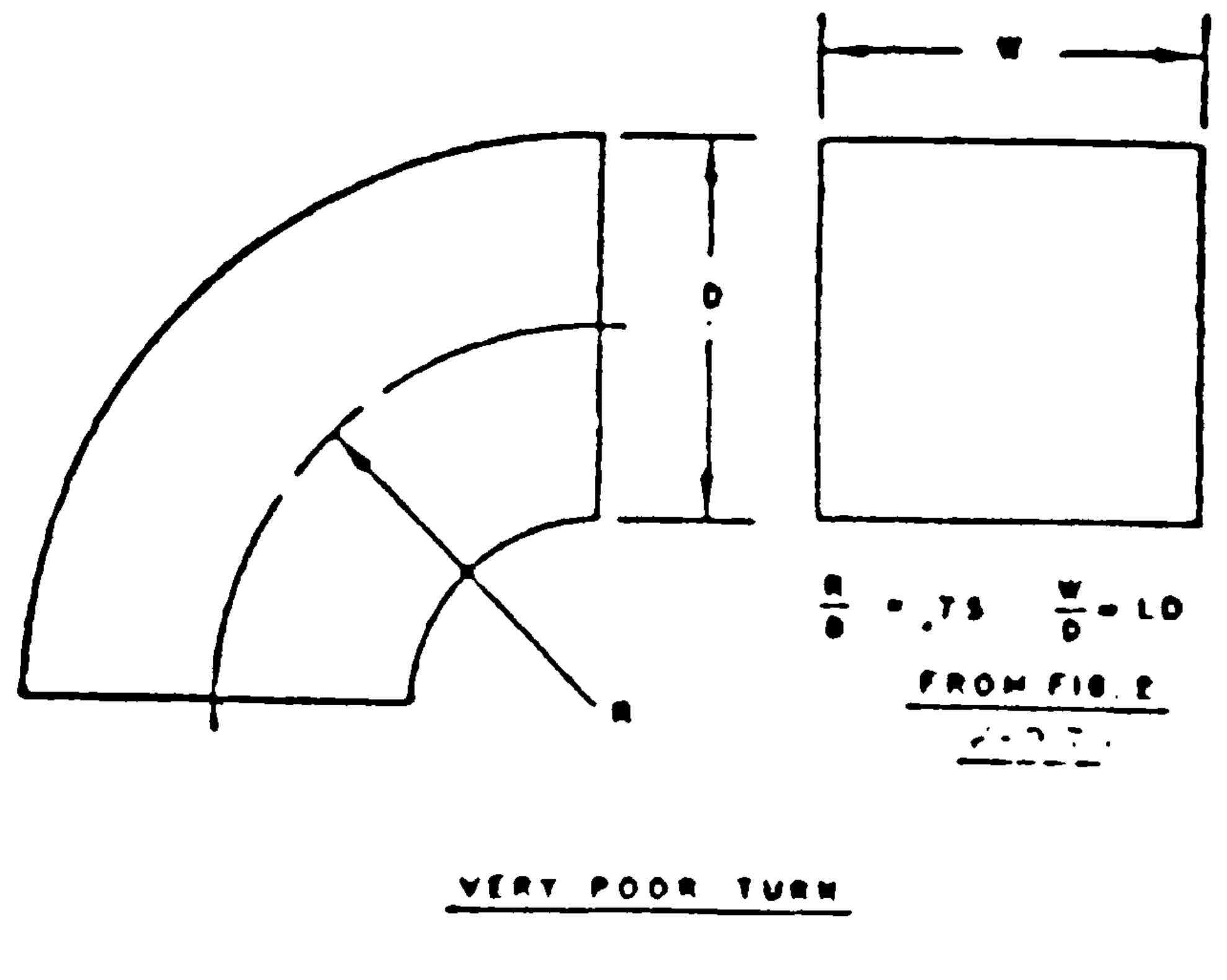
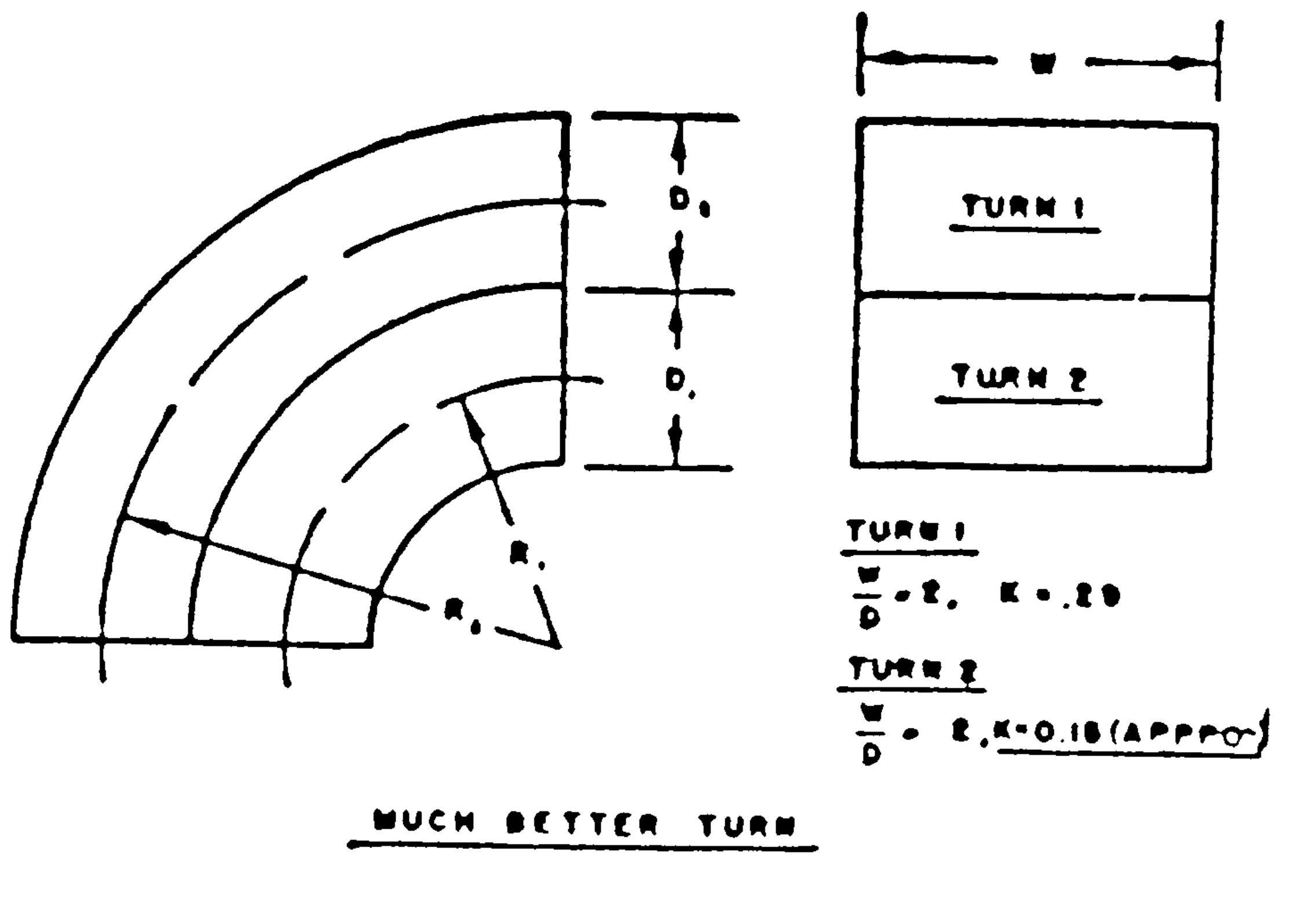


Figure 17



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Efficiency of an otherwise poor turn be made comparable to the best plain turn by using vanes of definite profile shape. These profiled vanes will give a $K = 0.15$ in a square turn of 90°. Reference 5 gives detailed information on the use of these contoured vanes. As a general rule, it will probably be best to try to avoid dividers and vanes since as high or higher efficiencies can be obtained through use of optimum aspect and radius ratios. They are mentioned here to indicate that there is an "out" when it seems inevitable that a poor turn will have to be tolerated.

The exit of a duct system must be designed to cause a minimum of disturbance of the general airflow in region of the exit. This is a matter of so proportioning the exit that the air leaving through it comes out smoothly and as nearly parallel to the flow of the main body of air as possible. Another function of the exit is that it is frequently used to control the flow through the duct. In such cases, the exit will be equipped with flaps to vary the exit area. An increase in exit area causes an increase in air flow through the duct. Examples of this can be seen in cowl flaps and radiator exit flaps. Under conditions where the velocity of the air passing the airplane is not sufficient to cause the proper amount of air to flow through the duct, the flaps may be opened wide (figs. 19 and 20).

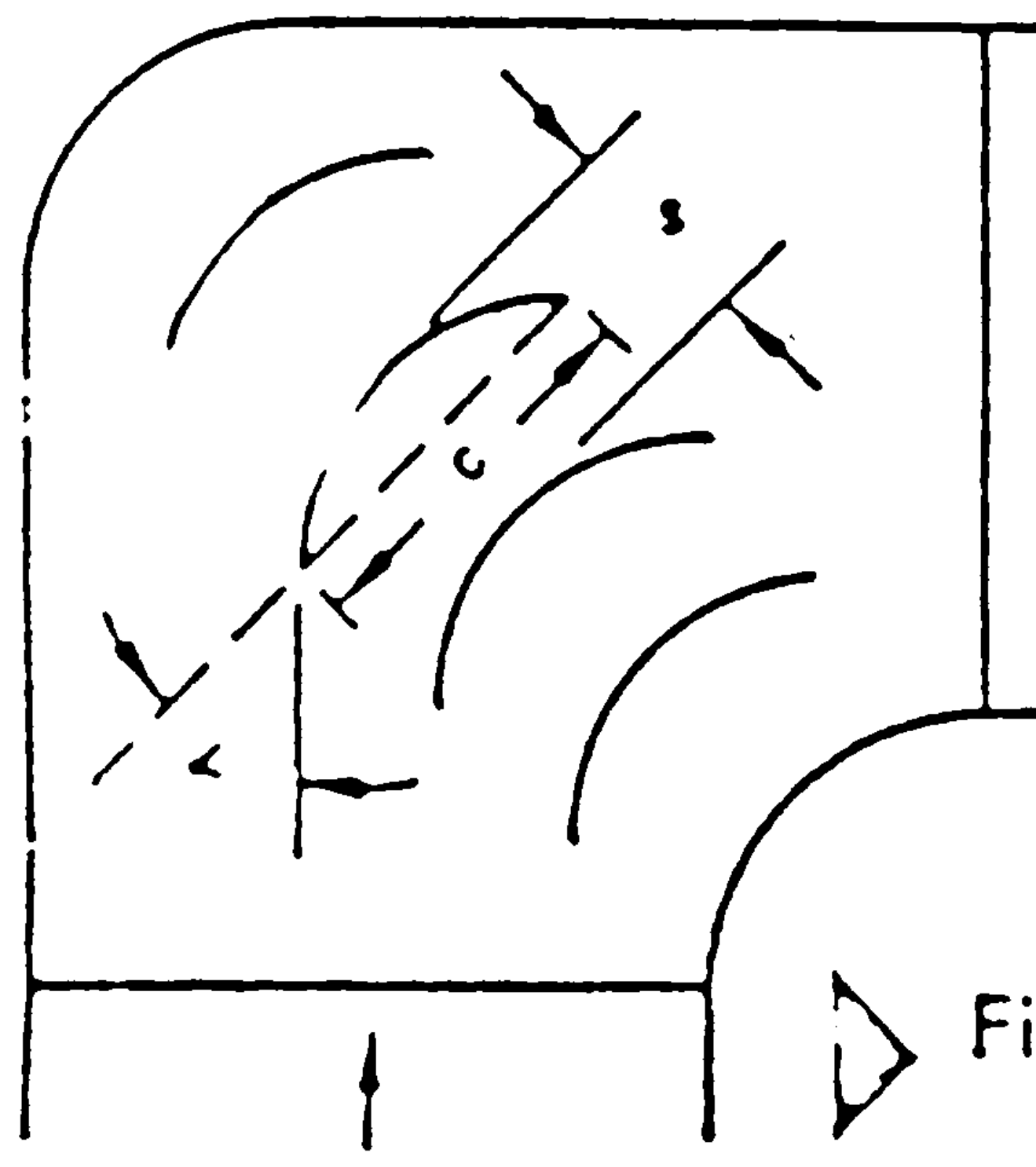
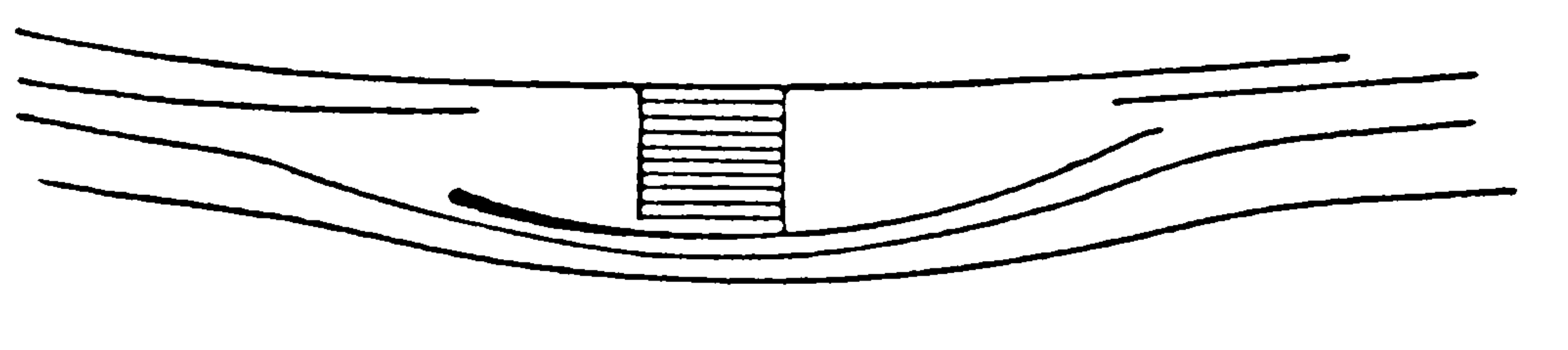


Figure 18 (left)

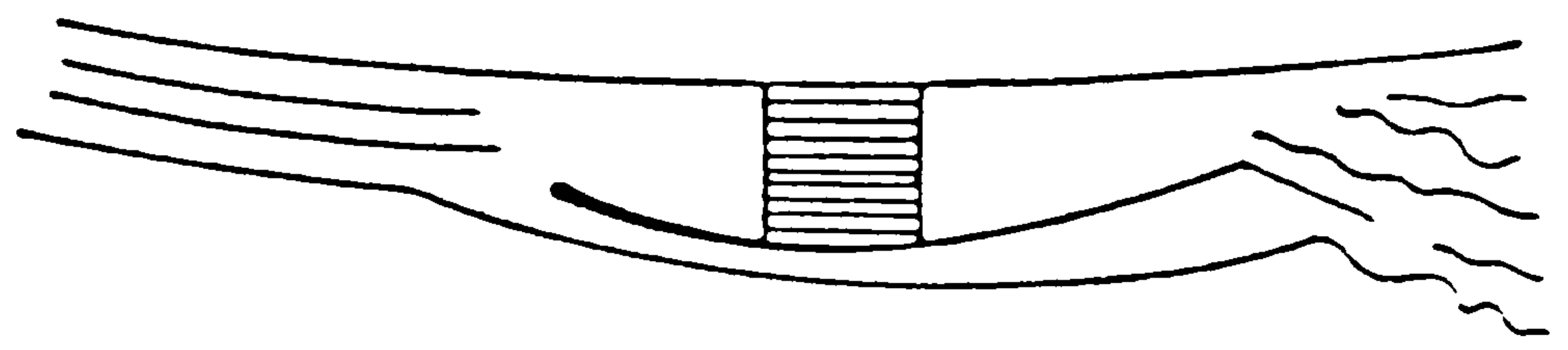
THE VANES ARE $\frac{1}{4}$ CIRCLE ARCS
∠ 45°
THE GAP CHORD RATIO* $\frac{S}{C}$ = 0.45
K = 0.20 (APPROX.)



DUCTED RADIATOR

HIGH SPEED CONDITION - FLAP IN NORMAL POSITION AND PRESSURE OF EXIT AIR EQUAL TO OUTSIDE AIR PRESSURE.

Figure 19



DUCTED RADIATOR

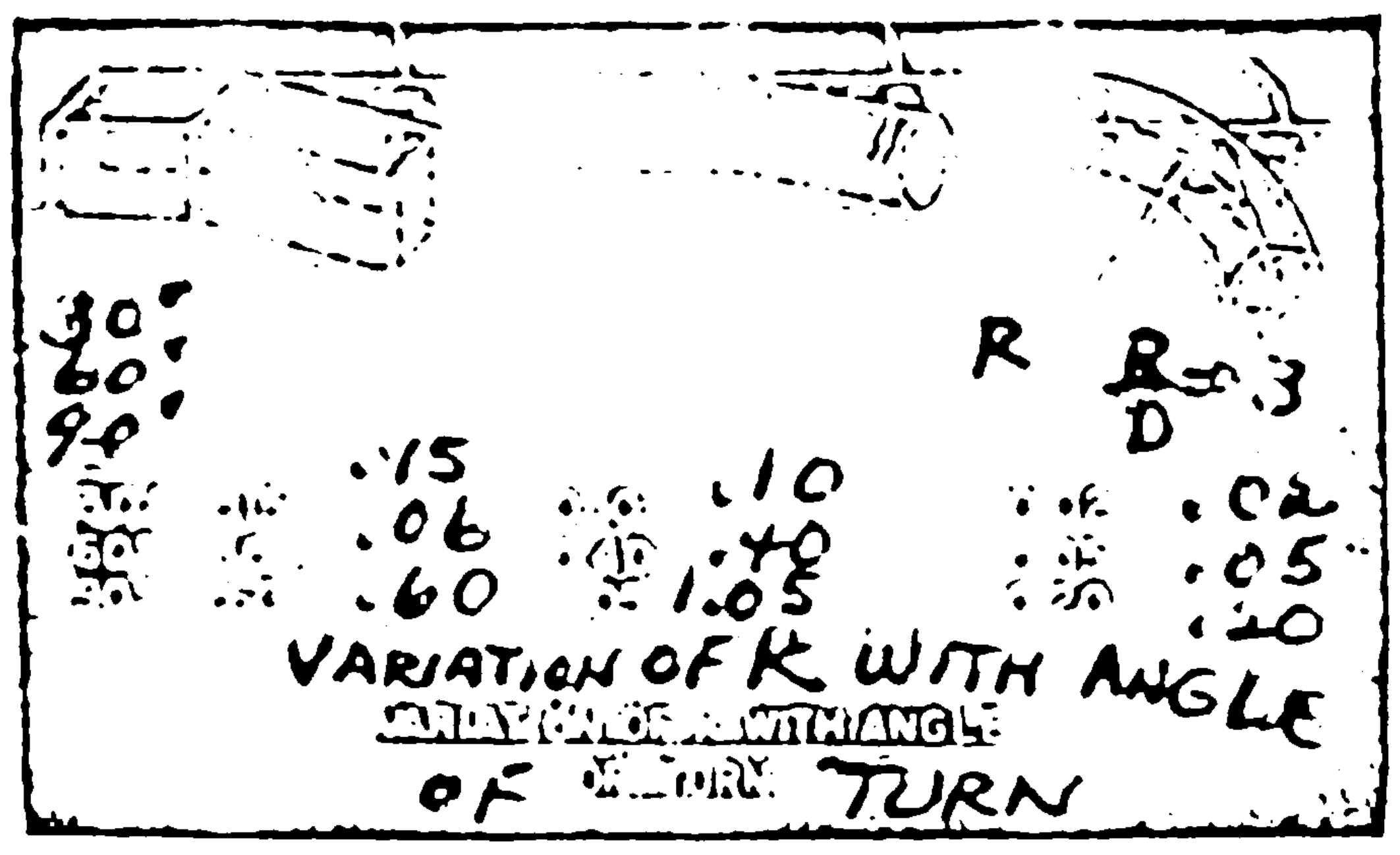
CLIMB OR OTHER CONDITION REQUIRING GREATER AIRFLOW THAN REDUCED PLANE SPEED WILL FURNISH FROM VELOCITY PRESSURE DROP ALONE.

Figure 20

Pressure Drop in System

The pressure drop in the radiator or in whatever the system is being designed to service is the starting point estimating the total drop of the duct stem. In the case of the radiator, the radiator itself determines the amount of flow required. Knowing this, we can estimate the entry size and velocity and the exit size for the design condition.

Next, the problem is to connect the entry to the radiator and the radiator



30°
60°
90°
R
$\frac{R}{D}$ = 3
.15
.06
.60
.10
.40
1.05
.02
.05
.10
VARIATION OF K WITH ANGLE OF TURN

Table 1

to the duct. If it is a system as simple as the one shown in figs. 19 and 20 the area back of the entry is expanded as outlined previously under entry design, passed through the radiator, and contracted until the static pressure at the exit is equal to the outside pressure. This contraction of the flow in the exit section serves to increase velocity and reduce pressure. The process is continued to the point of equalized pressure to cause a minimum of cross flow between the exit stream and the duct exit air. The condition of minimum cross flow gives lowest exit losses by causing a minimum of turbulence. To assist in obtaining parallel exit flow the exit walls should be parallel for a short distance prior to point of discharge.

For sake of illustration, refer to the previous example and add a few complications in the way of a turn on each side of the radiator plus a diffuser section as indicated in fig. 21.

(From example under heading of entry area)

$Q = 2500$ cfm $= 41.7$ cfs
$V = 300$ mph $= 440$ fps $=$ airplane speed
$V_1 = .5V = 220$ fps
$(1.467 \times V_{mph} = V'$ fps)

(1) Between stations 1 and 2 expansion takes place which makes $V_2 = 100$ fps. If expander is designed according to rules, the value of the loss coefficient through this section will be about $K_c = .05$ with respect to the exit velocity, at the expander or V_2 (fig. 6).

(2) From point 2 to point 3 is a turn of $\frac{R}{D} = 1.5$, $\frac{W}{D} = 2$. Losses in this turn are $K_c = .18$ with respect to V_3 (fig. 15).

(3) From point 3 to 4 the friction losses may be disregarded.

(4) From 4 to 5 is a diffuser, the area of which increases so as to reduce the velocity to 50 fps at V_5. The diffuser loss will be about the same as the expander loss or $K_c = .05$ with respect to V_5 (fig. 6).

(5) From 5 to 6 there is no change in velocity but there is a loss in static pressure across the radiator. The amount of this loss is determined from radiator specifications.

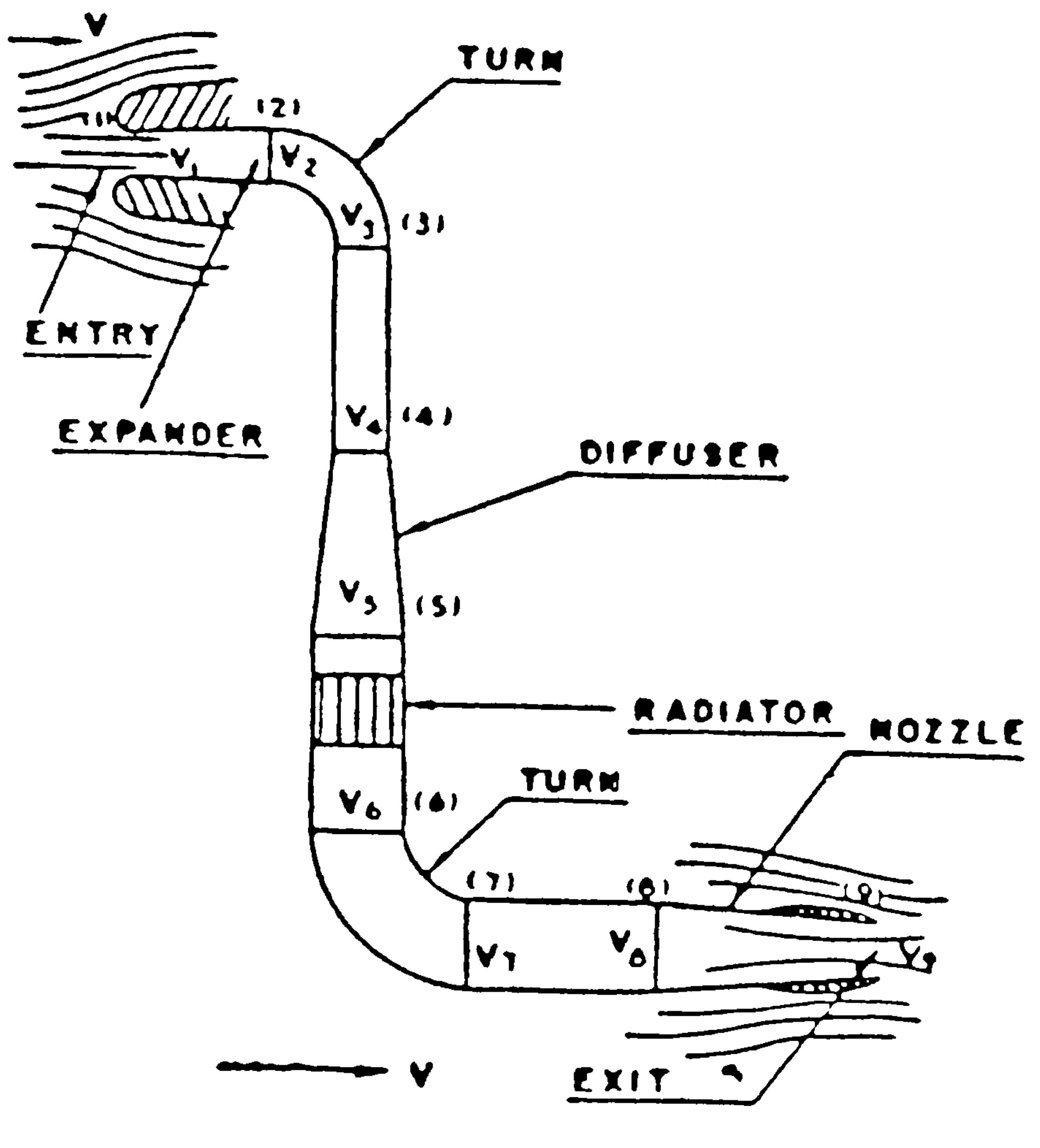
(6) From 6 to 7 is a turn of $\frac{W}{D} = 1$, $\frac{R}{D} = 2$, (square turn) having a loss with respect to V_7 of $K_c = .20$ (fig. 11).

(7) From 7 to 8 there are only friction losses which again may be disregarded.

(8) From 8 to 9 the loss is again small—the change in velocity and pressure will be taken up later. From the example concerning entry area it is known that the area at point 1 is .189 sq ft.

Having decided on the velocities desired at various places in the system, the area at these points can be determined by using the expression $Q = AV$, since Q is constant at 41.7 cfs throughout the duct. The values for the loss coefficient K may be selected from figs. 11, 15, and/or 6 for each section of the duct, and the loss in each section determined from the equation.

Figure 21



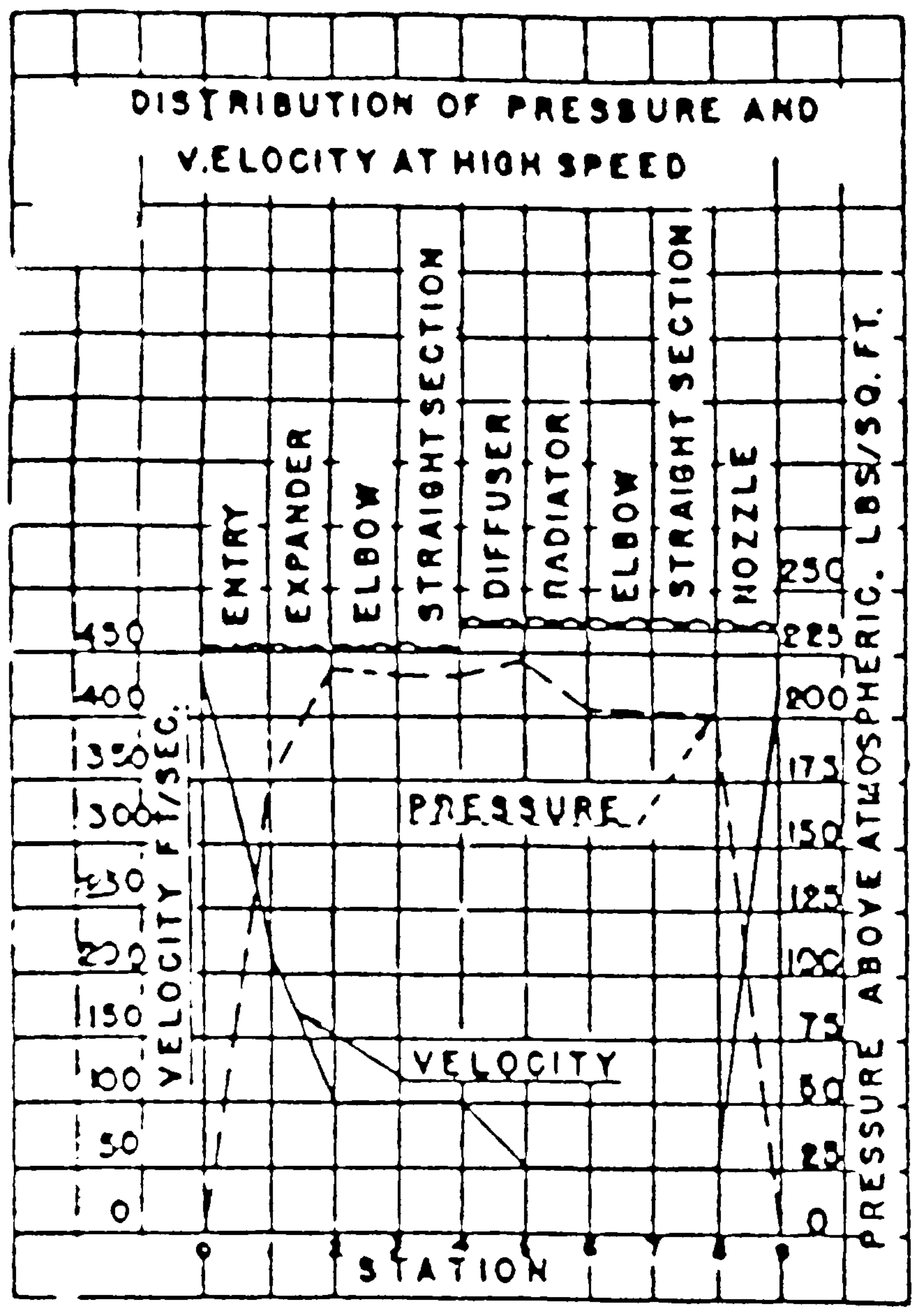


Figure 22

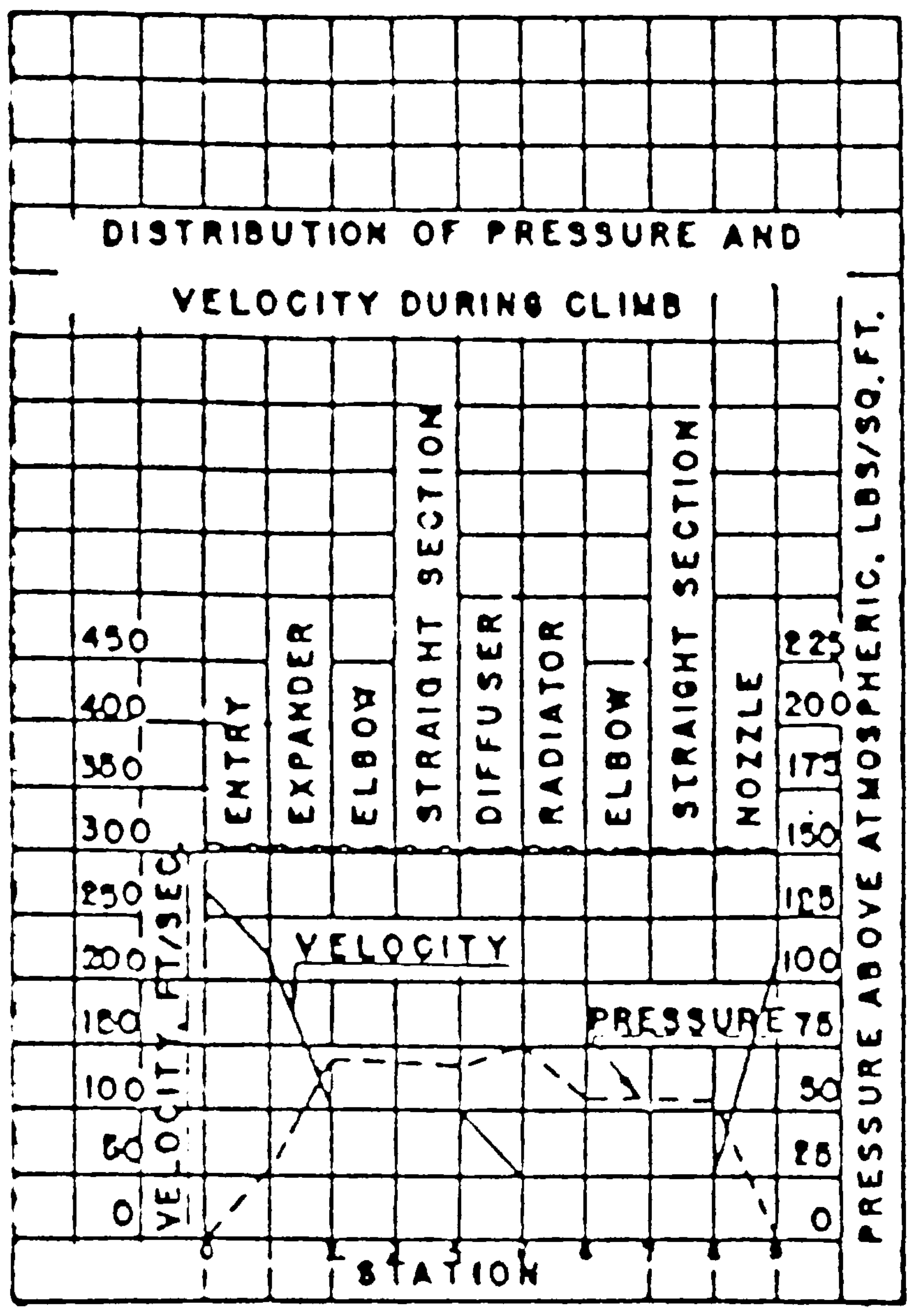


Figure 23

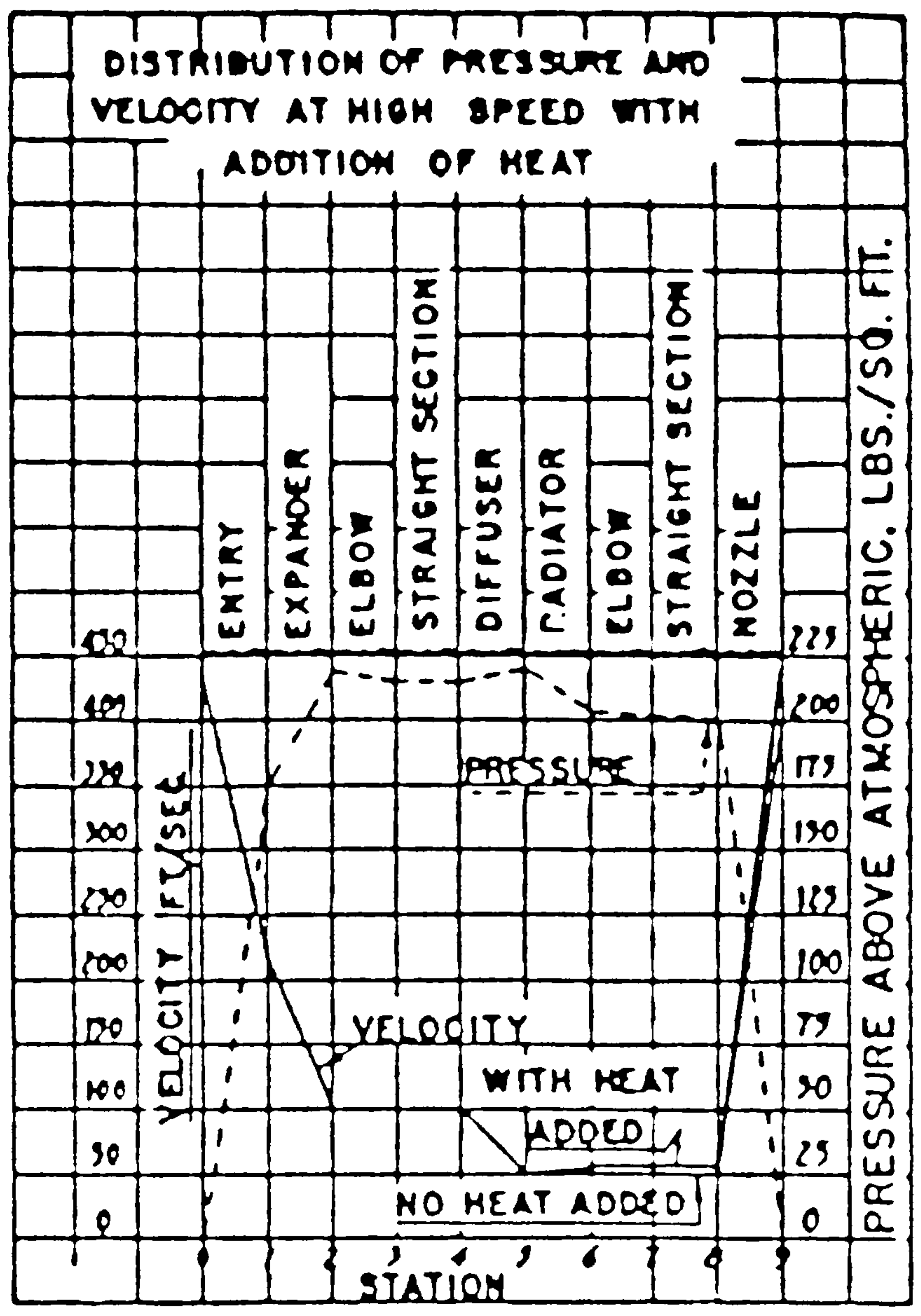


Figure 24

$\Delta_p = K\frac{1}{2}\rho V^2$ (loss expressed in terms of static pressure of psf)

The static pressure may be calculated by starting at the entry and working progressively through the system with the change in static head from point to point being equal to the change in velocity head.

$$p_2 - p_1 = \frac{1}{2}\rho V_1^2 - \frac{1}{2}\rho V_2^2$$

where: V = velocity in fps
ρ = density in lb per cu ft.

(Note: All pressures are measured above atmospheric unless otherwise stated.)

Sample calculations. Calculating our conditions at point 2 we have:

(a) Area

$Q = AV$ or $A = Q/V$

$$A = \frac{41.7}{100} = .417 \text{ sq ft}$$

(b) Available static head at point 2 = Available static head at entry + static head due to expander from 1 to 2.

$\frac{\rho}{2} = .001189$ for standard conditions

$$P_2 = (.001189 \times \overline{440}^2 - .001189 \times \overline{220}^2) + .001189 \times \overline{220}^2 - .001189 \times \overline{100}^2$$
$$= (230 - 57.5) + (57.5 - 11.89)$$
$$= 172.5 + 45.69$$
$$= 218.11 \text{ psf}$$

(c) Static pressure loss in entry and expander. From fig. 6 it is found that $K = .05$ (assuming that the expander divergence is within the limits recommended). The loss in respect to velocity at point 2 is

$$\Delta P = K(\frac{1}{2}\rho V_2^2)$$
$$= .05 \times .001189 \times \overline{100}^2$$
$$= .594 \text{ psf}$$

(d) Subtracting this loss from the available static head 218.11 — .594 = 217.52 psf. Actual static head at point 2.

This may be done for each section of the duct using these same equations except for the radiator. To determine the pressure loss through the radiator, the data furnished by the radiator manufacturer must be examined.

From the radiator specifications it may be given that a flow of 2500 cfm will cause a pressure drop of 4 in of water. Converting this to psf

$\frac{4}{12} \times 62.4 = 20.8$ psf (62.4 lb is wt. of one cu ft of water)

Tabulating the results—

sible external disturbance and to place the duct system in equilibrium.

The nozzle contracts the stream until the static pressure available has been converted to velocity head according to the following equation.

$$P + p_8 + q_8 = P + p_9 + q_9$$

P = Atmospheric pressure
p_8 = Static pressure at station 8
q_8 = Velocity head at station 8
p_9 = Static pressure at station 9
q_9 = Velocity head at station 9

Since P is the same at both points, it may be canceled, and p_9 is zero from the above conditions, the relations are:

$$P_8 + q_8 = q_9$$

TABLE II

Sta	V fps	A sq ft	K	Static Pressure Avail., psf	Δp psf	Static Pressure Actual, psf
0	440	—	—	—	—	—
1	220	.189	—	172.5	—	172.5
2	100	.417	.05	218.1	.594	217.5
3	100	.417	.18	217.6	2.14	215.4
4	100	.417	—	215.4	—	215.4
5	50	.834	.05	*224.4	.149	224.2
6	50	.834	—	224.2	20.8	203.4
7	50	.834	.20	203.4	.594	202.8
8	50	.834	—	202.8	—	202.8
9	50	.834	—	202.8	—	Zero

* The diffuser increases the available static pressure by 8.92 psf at this point.

Note: The figures in the column labeled "static pressure available, psf," represent the static pressure that would be developed if there were no losses. Those under the heading "static pressure actual, psf," include the losses.

In the above tabulation it may be noted that the nozzle area and velocity are still unknown. All that is known is that the exit pressure is to be atmospheric so as to cause the least possible external disturbance and to place the duct system in equilibrium.

or

$$202.83 + \frac{1}{2}\rho V_8^2 = \frac{1}{2}\rho V_9^2$$

Transposing and substituting values of ρ and V_8 we have $.001189\ V_9^2 = 202.83 + .001189 \times \overline{50}^2$

$V_9^2 = 171{,}000 + 2500$
$V_9^2 = 173{,}500$
$V_9 = 414$ fps = exit velocity

In order to determine the exit area the equation $A = Q/V$ may be used—

(*Continued on page* 210)

AIRPLANE DUCT DESIGN

(*Continued from page* 129)

$$A_9 = \frac{41.7}{414} = .101 \text{ sq ft} = \text{exit area}$$

The variation of pressure and velocity through the duct are shown graphically in fig. 22.

In order to evaluate the losses in the system, the pressure drop in each element is found and multiplied by the area on the exit side of the element. This gives the resistance to flow in lb which is reflected in just this number of lb of drag on the airplane.

Comparing these drags with the drag of the radiator gives the magnitude of the losses which are incurred in bringing air to the radiator and discharging it after its work is done. The figures are given in table III.

TABLE III

	A sq ft	Δp psf	Δp lb (Drag)
1	.189	——	——
2	.417	.594	.248
3	.417	2.14	.893
4	.417	——	——
5	.834	.149	.124
6	.834	20.8	17.35
7	.834	.496	.413
8	.834	——	——
9	.101	——	——

Total drag = 19.03 lb

Adding all losses with the exception of the radiator, the drag is found to be 1.678 lb.

Comparing this to the total drag, $\frac{1.678}{19.03} = 8.82\%$ of total loss is incurred in getting air to and from the radiator. (Note that this figure deals only with internal losses. Other losses due to external resistance are not included.)

Duct efficiency is calculated in a manner similar to any other efficiency. It is the ratio of the output divided by the input to the system. The drag of the radiator is the useful load on the system and the total drag of the system is the input. Therefore, the efficiency is:

$$\eta = \frac{\text{output}}{\text{input}} = \frac{17.35}{19.03} = 92.2\%$$

This is an efficient duct system and above losses are reasonable. This is largely due to operating the greater part of the duct at low velocities. The loss in any element of a duct system varies as the square of the velocity through the element,

$$\Delta p = K \times \frac{1}{2}\rho V^2$$

The case of a carburetor air duct or intake may seem to be a very different kind of duct to determine an efficiency for, but the same principles apply. Take for example—Pressure available at 200 mph = 102.3 psf = 19.7 in of water. Pressure loss to carburetor inlet (from test) = 3.5 in of water. Therefore, the input is 19.7 in of water pressure and the output is 19.7 — 3.5 = 16.2 in of water pressure. Then

$$\eta = \frac{16.2}{19.7} = 82\%$$

The duct system has been covered for the high speed condition; now it will be investigated to see if it will work satisfactorily at other conditions of flight. For example, the climb condition, where the velocity may be only .6 of high speed velocity.

The conditions are (assuming air requirements are constant)

$$V = 300 \times .6 = 180 \text{ mph} = 264 \text{ fps}$$
$$Q = 2500 \text{ cfm} = 41.7 \text{ cfs}$$

Since the air requirements are the same throughout the duct, the velocity conditions are likewise the same, except at the entry and exit. First, examine the entry. The entry area has not changed and since an entry velocity of 220 fps is needed, the entry velocity ratio is found to be—

$$\frac{V_1}{V} = \frac{220}{264} = .83$$

Referring to the section on entries (figs. 1-5), it is found that this condition is more critical than the high speed condition as far as the expansion angle 2θ is concerned. Under high speed conditions with $V_1/V_0 = .5$, the expander angle could have been 2θ = 13° max., but now it is found that the climb condition is critical and V_1/V_0 falls between .75 and 1.0, giving a maximum design angle of approximately 2θ = 9° if excessive losses are to be avoided.

In order to determine the new exit conditions, the pressure conditions in the system must be re-examined.

The available static pressure at entry is now:

$$P_1 = \left(\frac{1}{2}\rho V^2 - \frac{1}{2}\rho\ V_1^2\right)$$
$$= .001189 \times \overline{264^2} - .001189 = \overline{220^2}$$
$$= 82.7 - 57.5$$
$$= 25.2 \text{ psf}$$

Since the velocity requirements are the same the losses are the same, and at point 8, ready for the nozzle there is only 55.54 psf static pressure left instead of 202.83 psf as was available in the high speed case.

This means that there is much less pressure to be converted into velocity head and therefore the area is going to be larger. Using the same expression as in the high speed case—

$$P + p_8 + q_8 = P + p_9 + q_9$$

And again P is the same on both sides and may be dropped and likewise $p_9 = 0$, giving—

$$p_8 + q_8 = q_9$$

or

$$55.54 + \frac{1}{2}\ V_8^2 = \frac{1}{2}\ V_9^2$$

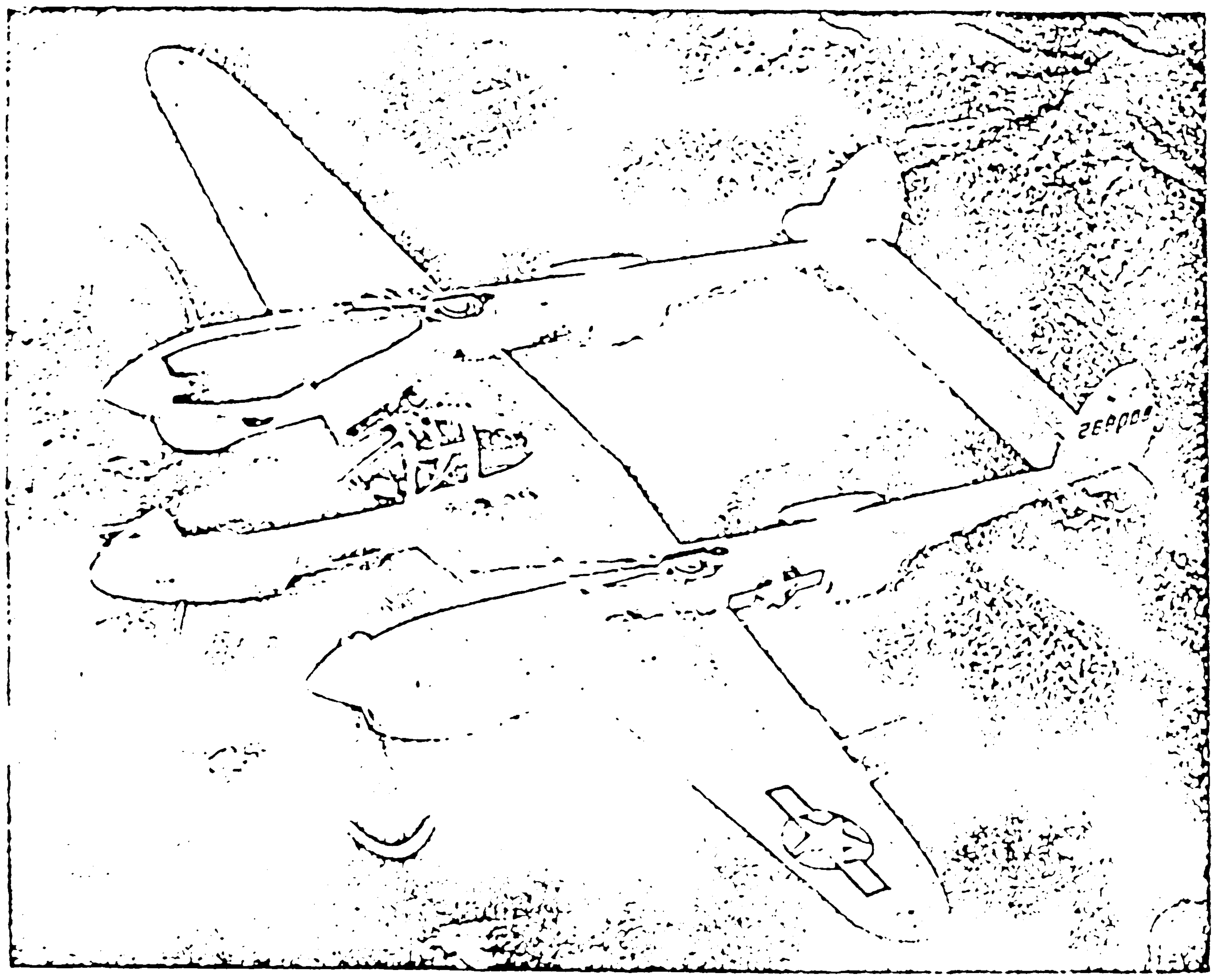
transposing and substituting values of ρ and V_8 gives—

$$.001189\ V_9^2 = 46800 + 2500$$
$$= 49{,}300$$
$$V_9 = 222 \text{ fps}$$

(*Continued on page* 213)

The P-38 strikes at Axis in shining metal skin. Eliminating painting saves production man-hours, lessens skin friction in flight. Areas painted black circumvent glare

Acme



(*Continued from page* 210)

And the exit area is—

$$A_o = 41.7/222 = .188 \text{ sq ft}$$

Tabulating our conditions throughout the system we have table IV

TABLE IV

Sta	V fps	A sq ft	K	Static Pressure Actual	Static Pressure Available	psf
0	264	—	—			—
1	220	.189	—	25.2 lb ft	25.2 lb ft	—
2	100	.417	.05	70.3	70.9	.594
3	100	.417	.18	68.16	70.3	2.14
4	100	.417	—	68.16	68.16	—
5	50	.834	.05	76.93*	77.08	.149
6	50	.834	—	56.13	76.93	20.8
7	50	.834	.20	55.54	56.13	.594
8	50	.834	—	55.54	55.54	—
9	222	.188	—	Zero	55.54	—

*Diffuser again adds 8.92 psf

The above tabulation is shown graphically in fig. 23 and illustrates clearly the effect of changing the area of the exit in controlling the flow through the duct system. If the critical conditions are the ones in this example, it is necessary to design the exit so that its area can be controlled between the limits of .101 sq ft for high speed and .188 sq ft for climb.

Maintaining Favorable Ratio

In cases of lower speeds or wider speed ranges, it may be necessary to maintain a favorable V_1/V ratio at the lower speed to enlarge our entry. If we do this the velocity ratio will be reduced at the high speed condition and more fairing will be needed. Also due to this V_1/V change the entry losses may change and the pressures throughout the system may have to be recalculated for the new initial static head. If the lower speed is below that capable of furnishing sufficient pressure drop to force the required airflow through the system, the total available pressure drop may be increased by the use of flaps at the exit. Well designed flaps will increase the available pressure drop by approximately one-third in most installations. (See figs. 19 and 20).

The special case of effect of addition of heat by a radiator will be discussed, since it is a very important application of ducts. It will be applied to the high speed case, for example, and its effects on the exit conditions shown.

The conditions upstream from the radiator are identical. In the radiator the air passing through it, absorbs heat, decreases in density and increases in volume at approximately constant pressure. It has been found that these processes can be considered as taking place just aft of the radiator without appreciable error. Therefore, assuming a rise in air temperature of 50° F and applying $\frac{V_o}{t_o} = \frac{V_a}{T_a}$ subscript $_o$ meaning before addition of heat subscript $_a$ meaning after addition of heat

V in cu ft

T in F° absolute

$T_o = 59°$ F absolute

$T_a = 519 + 50 = 569°$ F absolute

$$\frac{V_o}{319} \quad \frac{V_a}{569}$$

$$\frac{V_a}{V_o} = \frac{569}{519} = 1.095 \text{ ratio of expansion}$$

Since the Q before heating was 41.7 cfs it is, after heating

$$Q_a = 1.095 \times 41.7 = 45.6 \text{ cfs}$$

The density has decreased from .002378 slugs per cu ft to same extent that our volume has increased.

$$\frac{.002378}{1.095} = .002170 \text{ slugs per cu ft or } \frac{\rho}{2} = .001085$$

The velocity has changed as a result of the addition of heat and now becomes:—

$$V_a = Q_a/A$$

$$V_a = \frac{45.6}{.834} = 54.7 \text{ fps}$$

Since the velocity has increased, larger losses will be incurred in the elbow from point 6 to point 7 (fig. 21). However, the lowered density tends to reduce the losses.

$$\Delta P = Kc \times \frac{1}{2} \rho V^2$$

$$= .20 \times .001085 \times \overline{54.7^2}$$

$$= .65 \text{ psf}$$

While the increase in pressure drop in the elbow is not very important at high speed, it is well to keep such pressure drop increases in mind where a relatively small increase of this nature can be a large proportion of the duct drag and may affect duct performance at low speeds.

Deducting the elbow loss from the available static head

$$203.42 - .65 = 202.77.$$

Using the same equation as previously used for obtaining nozzle velocity at zero static head

$$p_o + q_o = q_o$$

or

$$202.77 + .001085 \times \overline{54.7^2} = .001085 \; V_o^2$$

$$V_o^2 = 187{,}300 + 3000 = 190{,}300$$

$$V = 436 \text{ fps}$$

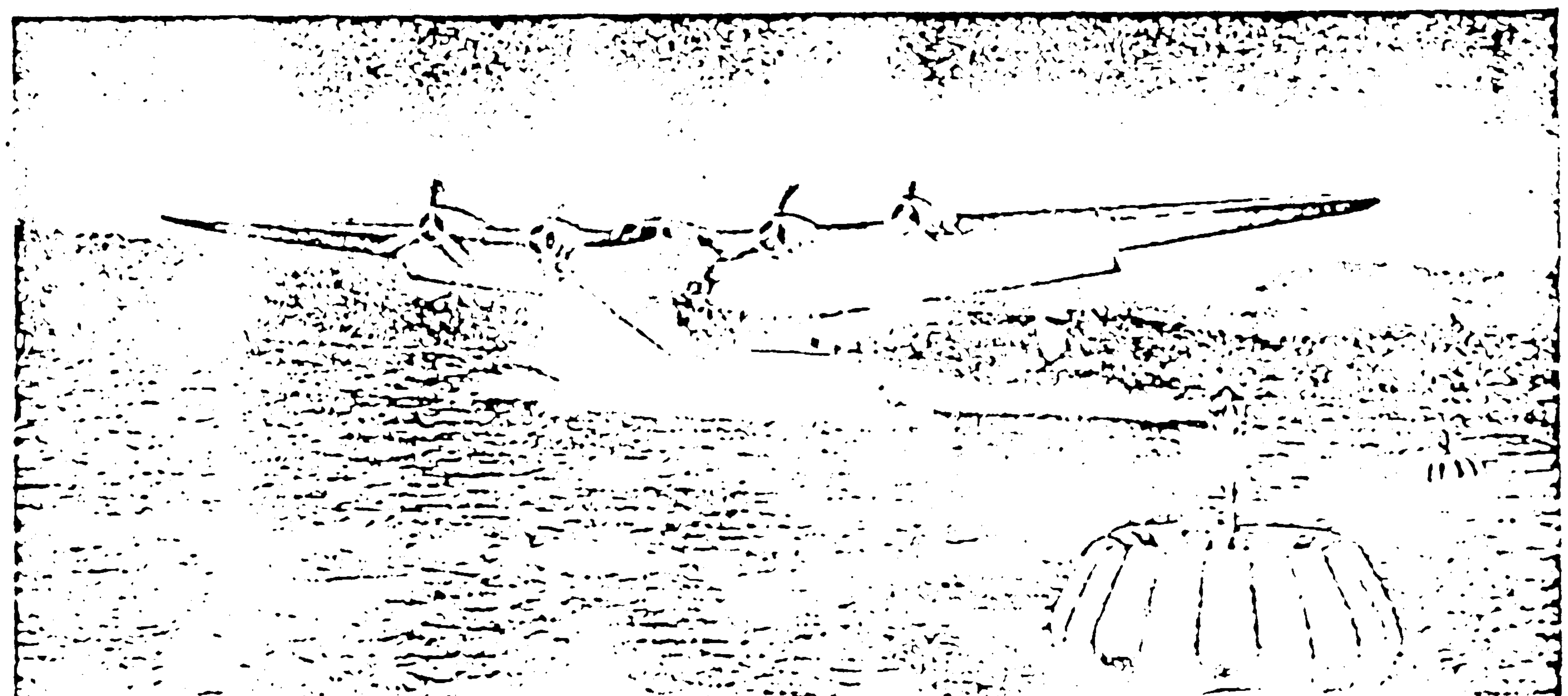
Exit area required with heating becomes

$$A_o = \frac{45.6}{436} = .1045 \text{ sq ft}$$

Comparing the area of .1045 sq ft with heating to the cold radiator exit area of .101 sq ft found in the original high speed example, it is seen that a larger area is needed to handle the exit air or that less velocity conversion is necessary. Comparing the velocities, it is found that the original speed was 414 fps at the exit but that with heating the speed becomes 436 fps resulting in a decrease in the drag of the radiator duct system due to heating.

Pressure and Velocity Variations

The variations of pressure and velocity are shown graphically in fig. 24. Note the shaded area on the velocity curve. This area is the difference be-



Visible for three miles, these new buoys enable planes to land and take off at night. Using a secret frequency, a pilot many miles away can actuate its lights from his plane tween the heated radiator and the cold one, showing the increased velocity due to heating.

In general the same rules apply to design of carburetor ducts as to other ducts, however practical consideration may make it desirable to deviate from the usual design practices.

On the subject of elbows or turns in the carburetor duct, it is felt by many that a sharp turn is more efficient than a smooth one. This does not seem to be borne out by experimental data. Said data seem to show that the sharp square turn is always less efficient than a smooth one, and that the smooth one will give better velocity and pressure distribution. One of the factors that may enter into this is that, in using a sharp square turn, it is usually possible in most carburetor duct installations to use a longer length of straight pipe following the elbow before the carburetor. The use of a straight length of pipe following an elbow always improves both the velocity and pressure distribution. Tests show that this length should be about four times the narrow cross-section dimension as a minimum, but if this is not possible, as much straight length should be used as space will allow.

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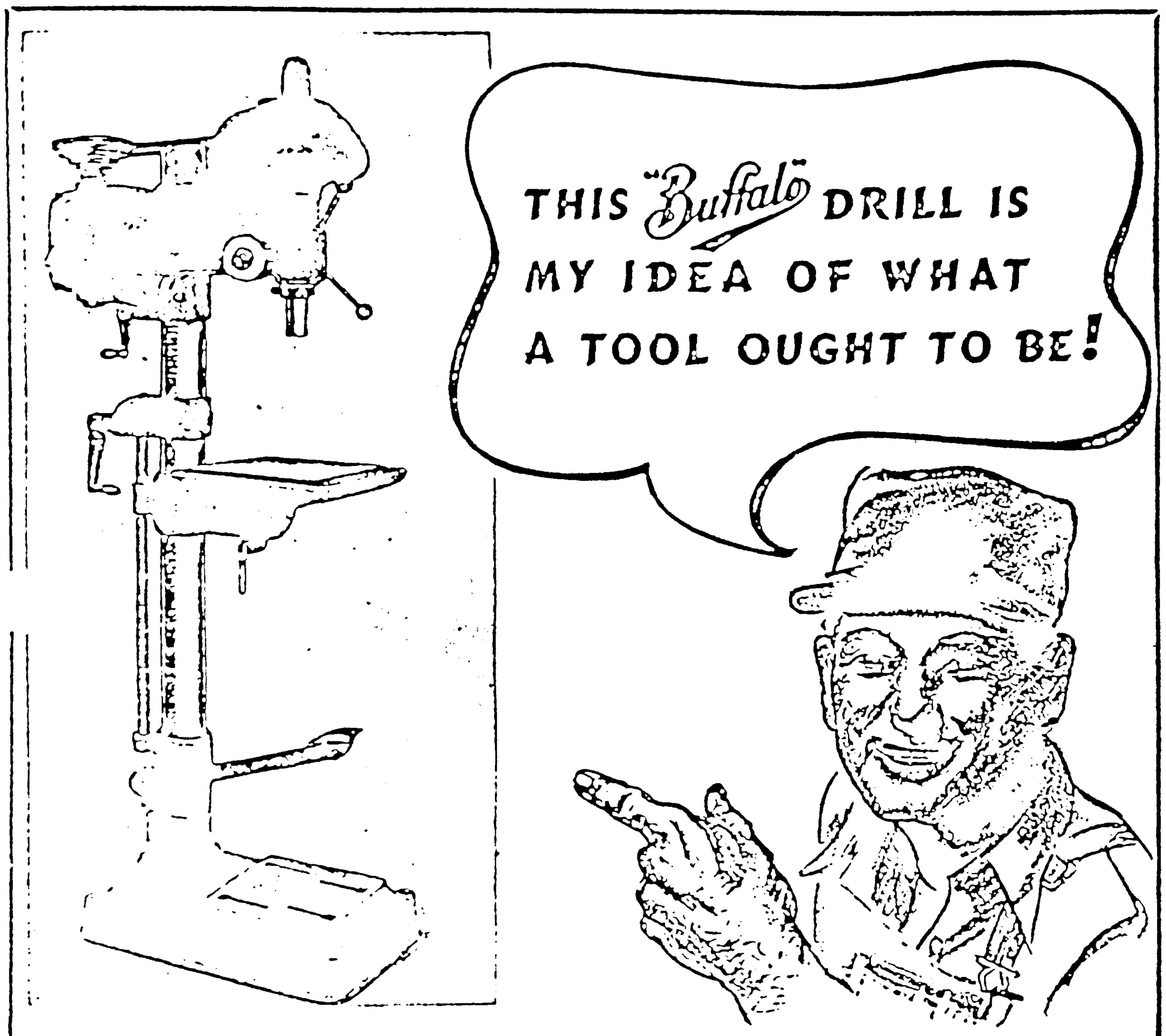
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DESIGNING LIGHTER ELECTRICAL EQUIPMENT

(*Continued from page* 103)

This is accomplished by cutting out the starting resistor with either a definite time relay or a counter emf relay. (The functions of these devices will be described in a subsequent article on electrical machinery fundamentals.)

Reversing Control

The more versatile contactor control is of the reversing type which has several sub-divisions and is usually identified with motor control. These are for full-voltage shunt, series, and compound-wound motors, both with and without dynamic braking.

Applications of this motor control include propellers, landing flap, antenna reel, bomb hoist and wing fold.

Fig. 5 shows two single-pole, single-throw contactors, mechanically interlocked so that if one contactor is energized the other cannot be closed. This combination can be used as a full-voltage reversing controller for a split-series, shunt, or compound motor as shown in figs. 6 and 7. It can also be used as a full-voltage reversing dynamic-braking motor controller for split series field motors, by the use of two sets of two single-pole, single-throw contactors. In the latter case, dynamic

(*Continued on page* 217)